Sensing with Quantum Light

754. WE-Heraeus-Seminar

26 Sep - 29 Sep 2021
hybrid at the Physikzentrum Bad Honnef

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

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

Aims and scope of the 754. WE-Heraeus-Seminar:

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

The area of quantum sensing is considered to be one which most likely is going to deliver real-world applications and products soon. Sensing with light in the form of imaging, microscopy, spectroscopy or other interferometric methods has always played an enormous role. Nowadays, the utilization of non-classical states of light, such as squeezed, sub-Poissonion or entangled light, promises to practically overcome the limits imposed by classical light sensing technologies.

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

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

Scientific Organizers:

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

Introduction

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Registration:

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

Program

Program

Sunday, 26 September 2021

16:00 – 21:00	Registration	
from 18:00	*BUFFET SUPPER / Informal get together*	
19:30 – 22:00	**discussions**	

Monday, 27 September 2021

07:45 – 08:45	*BREAKFAST*	
08:45 – 09:00	Scientific organizers	**Welcome and Organization**

Session I: Chair: Leonid Krivitsky

09:00 – 09:35	Roman Schnabel T1	**Squeezed light – now exploited by all gravitational-wave observatories**
09:35 – 10:10	Frank Schlawin T2	**Quantum metrology of two-photon absorption**
10:10 – 10:45	Ulrik L. Andersen T3	**Optical quantum sensing beyond the NOON state limit**
10:50 – 11:20	*COFFEE BREAK* / **discussion**	

Session I: Chair: Roman Schnabel

11:20 – 11:55	Marco Genovese T4	**New applications of twin beams as a quantum tool: from quantum reading to quantum conformance test**
11:55 – 12:30	Milena D'Angelo T5	**Toward quantum 3D imaging devices**
12:30	*LUNCH*	

Program

Monday, 27 September 2021

Session II: Chair: Ulrik Andersen

14:00 – 14:35	Marco Barbieri T15 (online)	**Semiparametric estimation in Hong-Ou-Mandel interferometry**
14:35 – 14:55	Juan Villabona-Monsalve C1 (online)	**Quantum Light for Sensing of Organic and Biological Materials**
14:55 – 15:15	Dmitry Tabakaev C2 (online)	**Spatial properties of entangled two-photon absorption**
15:20 – 15:50	*COFFEE BREAK /* **discussion**	
15:50 – 16:50	**Poster Flash** **Chair: Sven Ramelow**	
16:50 – 18:30	**Online Poster session I**	
18:30	*DINNER*	
19:30 – 22:00	**discussions**	

Program

Tuesday, 28 September 2021

08:00	*BREAKFAST*	

Session III: Chair: Marco Genovese

09:00 – 09:35	Jeff Ou T7 (online)	**Unbalanced Interferometers for Sensing**
09:35 – 10:10	Shigeki Takeuchi T8 (online)	**Efficient entangled photon sources and their applications**
10:10 – 10:45	Leonid Krivitskiy T9	**Broadband diffraction of correlated photons from crystal superlattices**
10:50 – 11:20	*COFFEE BREAK* / **discussion**	

Session III: Chair: Joachim von Zanthier

11:20 – 11:55	Maria Chekhova T10	**Biphotons from Ultrathin Sources**
11:55 – 12:30	Galiya Kitaeva T11 (online)	**Quantum correlated optical - terahertz biphotons: study and possible applications**
12:30 – 12:40	**Conference Photo** (in front of the Physikzentrum/Main entrance)	
12:40	*LUNCH*	

Session IV: Chair: Milena D'Angelo

14:00 – 14:20	Chiara Lindner C3	**Quantum Fourier-transform Infrared Spectroscopy**
14:20 – 14:40	Helen Chrzanowski C4 (online)	**Mid-Infrared Microscopy via Position Correlations of Undetected Photons**
14:40 – 14:50	*SHORT BREAK*	

Program

Tuesday, 28 September 2021

14:50 – 15:10	Elkin Santos C5	**Near-Field Subdiffraction Resolution Quantum Imaging with Undetected Photons**
15:10 – 15:30	Andrei Nomerotski C6 (online)	**Quantum-assisted optical telescopes**
15:30 – 16:00	*COFFEE BREAK /* **discussion**	
16:00 – 17:30	**Online Poster session II**	
17:30 – 18:30	**Poster prize jury**	
18:30	*HERAEUS DINNER at the Physikzentrum* *(cold & warm buffet, with complimentary drinks)*	

Program

Wednesday, 29 September 2021

08:00	*BREAKFAST*	

Session V: Chair: Frank Schlawin

09:00 – 09:35	Xiaoying Li T14 (online)	**Quantum Interference Recovered by Broadband Amplitude Measurement in an Unbalanced SU(1,1) Interferometer**
09:35 – 10:10	Alfred U'Ren T6	**Towards Practical Quantum Optical Coherence Tomography**
10:10 – 10:45	Robert Fickler T16 (online)	**Twisted NOON States for Angular Super-Resolution**
10:50 – 11:20	*COFFEE BREAK* / **discussion**	

Session V: Chair: Roman Schnabel

11:20 – 11:55	Joachim von Zanthier T13	**Quantum imaging with incoherently scattered light**
11:55 – 12:30	Dan Oron T14 (online)	**Heralded spectroscopy reveals exciton-exciton correlations in single colloidal nanocrystals**
12:30 – 12:40	Scientific organizers	**Closing remarks and poster awards**
12:40 – 14:00	*LUNCH*	

End of Seminar / Departure

Posters

Poster Session I Monday 16:50 – 18:30 CET

1	Foroud Bemani	**An optomechanical force sensor with feedback-controlled in-loop light**
2	Vira Besaga	**Development and characterization of a highly non-degenerate polarization-entangled Sagnac photon pair source**
3	Patrick Cameron	**Shaping photon pair correlations with an SLM**
4	Marion Cromb	**Revealing and concealing entanglement with noninertial motion**
5	Konstantin Dorfman	**Multidimensional sensing of hot Rb vapor with squeezed light**
6	Stefan Frick	**Quantum Rangefinding**
7	Paul Kaufmann	**Broadband Mid-IR Spectroscopy with Near-IR Grating Spectrometers**
8	Marta Gilaberte Basset + Sebastian Töpfer	**Quantum Holography with Undetected Light**
9	Valerio Flavio Gili	**Scanning Quantum Microscopy**
10	Björn Haase	**Evaluation of incoherent seeding on the performance of nonlinear interferometers**
11	Joshua Hennig	**Towards low-cost nonlinear interferometry**
12	Florian Herbst	**Imaging with undetected photons in MIR with large-aperture nonlinear crystals**
13	Aiman Khan	**Fundamental Limits on Estimation of Molecular Parameters Using Entangled Photon Spectroscopy**

14	Pawan Kumar	**Integrated nonlinear quantum interferometer with parity-time symmetry**
15	Jachin Kunz	**Broadband Fourier-transform infrared spectroscopy with visible Light**

Poster Session II Tuesday 16:00 – 17:30 CET

16	Mirco Kutas	**Terahertz material characterization with visible photons**
17	Arunava Majumder	**Advances inQuantumMetrology for Precise Measurements**
18	Arahata Masaya	**A wavelength variable visible-infrared photon pair source via spontaneous parametric downconversion in the mid-infrared region**
19	Alexander Mikhaylov	**Two-photon excitations with time-energy entangled photon pairs**
20	Yu Mukai	**Complex transmittance measurements using quantum Fourier-transform infrared spectroscopy**
21	Jens Arnbak Holbøll Nielsen	**Phase sensing using with squeezed states of light**
22	Raphael Nold	**A Quantum Optical Microphone in the Audio Band**
23	Sharam Panahiyan	**Controllable discrete-time quantum walk with twisted light**
24	Anna Paterova	**Nonlinear interferometry for a broadband infrared sensing**
25	Franz Roeder	**Two-colour broadband SU(1,1) – interferometry with dispersion engineered integrated PDC sources**
26	László Ruppert	**High-precision multiparameter estimation of mechanical force by quantum optomechanics**
27	Philipp Stammer	**High photon number entangled states and coherent state superposition from extreme-UV to far-IR**

Poster Session II Tuesday 16:00 – 17:30 CET

28	Andres Vega	**Metasurface-assisted quantum ghost polarimetry**
29	Andreas Volkmer	**Towards QuantumCARS micro-spectroscopy: Interferometric hyperspectral CARS imaging based on broadband correlated photon pairs**
30	Venkata Jayasurya Yallapragada	**Exciton interactions in semiconductor nanocrystals uncovered by spectrally resolved photon counting**
31	Ivan Zorin	**Mid-infrared light for non-destructive testing**

Abstracts of Lectures

(in alphabetical order)

Optical quantum sensing beyond the NOON state limit

Jens Arnbak Nielsen, Jonas S. Neergaard-Nielsen, Tobias Gehring and Ulrik L. Andersen
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Accurate measurements of different physical parameters including length, velocity and displacement can be attained through optical phase estimation. It has been known for numerous years that the precision or sensitivity of such phase measurements can be largely improved by using entangled or squeezed states of light as demonstrated in gravitational wave interferometry [1] and non-linear microscopy [2].

A fundamentally interesting question is "What is the optimal measurement strategy for phase sensing?". Using coherent states of light, the optimal scaling for the sensitivity is $1/N^{½}$ where N is the average number of photons. This, so-called shot noise scaling, can be beaten using NOON states which are known to give rise to a 1/N scaling – the so-called Heisenberg scaling. Numerous demonstrations of NOON state phase sensing have been conducted but only single experiment [3] has demonstrated sensitivity beyond the shot noise, and all experiments produced the NOON states in a probabilistic fashion.

In this presentation, we discuss a demonstration of quantum phase sensing based on deterministically prepared squeezed states followed by homodyne detection that not only beats the shot noise limited sensitivity but also beats the ideal NOON state sensitivity. In other words, we show that it is possible to attain Heisenberg scaling with a sensitivity that breaks the NOON state sensitivity using solely Gaussian states and Gaussian measurements with a photon number of more than ten.

References

(1) M. Tse et al, Phys. Rev. Lett. 123, 231107 (2019)
(2) R. B. de Andrade et al, Optica 7, 470, 2334 (2020)
(3) S. Slussarenko et al, Nature Photon. 11, 700 (2017)

Semiparametric estimation of Hong-Ou-Mandel interferometry

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Two-photon Hong-Ou-Mandel interference is the key effect that enables many quantum technologies based on photons and their manipulation. Its distinctive dip profile has a characteristic length remarkably dictated by the two-photon wavepacket, not by the wavelengths, ensuring stable and reliable operation. The actual wavefunction can be retrieved by a series of multiple Hong-Ou-Mandel profiles, however, with a single acquisition, some information can nevertheless be extracted; this can still be an appropriate regime for estimating specific quantities.

Even if we wish to isolate one particular parameter of the wavefunction, e.g. one of its moments, the estimation will unavoidably depend on the whole function, thus requiring, in principle, infinitely many other parameters for its full description. This apparently unsolvable problem has an elegant and efficient solution in semiparametric estimation. In standard parameter estimation one has to fix a statistical model with a finite number of parameters. On the contrary, the theory of semiparametric estimation deals with models with an infinity of degrees of freedom.

We apply the theory of semiparametric estimation to a Hong-Ou-Mandel interference experiment with a spectrally entangled two-photon state generated by spontaneous parametric downconversion. Thanks to the semiparametric approach we can evaluate the Cramér-Rao bound and find an optimal estimator for a particular parameter of interest without assuming perfect knowledge of the two-photon wave function, formally treated as an infinity of nuisance parameters.In particular, we focus on the estimation of the Hermite-Gauss components of the marginal symmetrised wavefunction, whose Fourier transform governs the shape of the temporal coincidence profile. We show that negativity of these components is an entanglement witness of the two-photon state.

References

[1] C. K. Hong, Z. Y. Ou, and L. Mandel, Measurement of subpicosecond time intervals between two photons by interference, Phys. Rev. Lett. 59, 2044 (1987).
[2] M. Tsang, Semiparametric estimation for incoherent optical imaging, Phys. Rev. Research 1, 033006 (2019).
[3] V. Cimini, F. Albarelli, I. Gianani, and M, Barbieri, Semiparametric estimation of Hong-Ou-Mandel interferometry, *submitted* (2021)

Biphotons from Ultrathin Sources

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When spontaneous parametric down-conversion (SPDC) occurs in a very thin nonlinear layer, the longitudinal momentum of the pump does not have to be conserved, and the daughter photons – biphotons - have almost unbounded frequency and angular spectra [1]. At the same time, if the pump is narrowband and not too tightly focused, the frequencies and the angles of emission for signal and idler photons are anti-correlated. These features make SPDC in strongly nonlinear ultrathin layers a useful source for correlated imaging and spectroscopy.

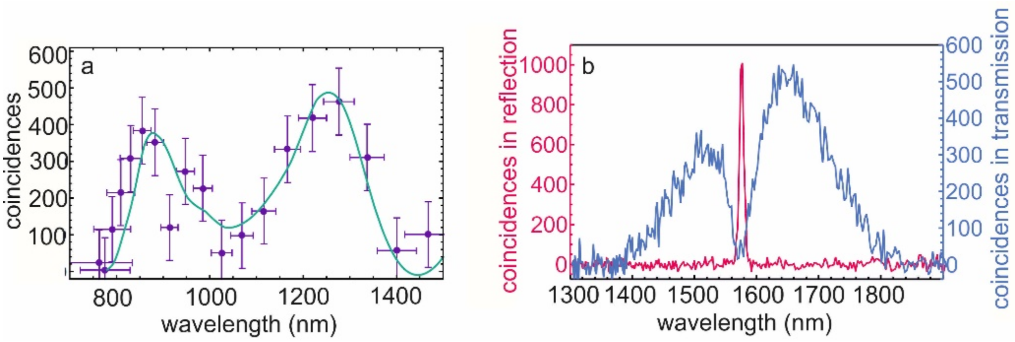

Fig. 1. SPDC spectra of a GaP film pumped at 515 nm (a) [2] and of an LN metasurface pumped at 788 nm (b) [3].

For instance, Fig.1 shows the SPDC spectra of a 400 nm layer of GaP (a) and a lithium niobate (LN) metasurface (b) in transmission (blue) and reflection (red). The spectra show the etalon fringes of the layer (a) and a Mie-like resonance of the metasurface (b), although the fluorescence of the samples exceeds the biphoton rate by two orders of magnitude. The spectra are visible due to the registration of coincidences instead of single counts. Here, spectroscopy is applied to the spectra of SPDC itself, but it can be also used to study an external sample in the presence of bright background. Note that no tuning of the crystal or the pump is needed. In the same fashion, biphotons from ultrathin layers can be used for correlation imaging.

References

[1] C. Okoth et al., Physical Review Letters 123, 263602 (2019).
[2] T. Santiago-Cruz et al., Optics Letters 46, 653-656 (2021).
[3] T. Santiago-Cruz, A. Fedotova et al., Nano Letters 21, 4423-4429 (2021).

Mid-Infrared Microscopy via Position Correlations of Undetected Photons

Inna Kviatkovsky[1], Helen M Chrzanowski[1], Sven Ramelow[1,2]

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The functionality to image samples in the mid to far infrared (IR) holds the promise of new perspective on problems of tremendous biological and industrial relevance. The principle limitation, however, remains one of detection, with mid-IR imaging technology being prohibitively expensive, technically demanding and suffering from poor sensitivity and resolution. The absence of a good detection option has lead to numerous approaches that exploit wavelength conversion to the visible regime, where one can enjoy the comparable maturity of CCD and CMOS technology driven by the life sciences. Here, we demonstrate how quantum non-linear interferometry [1] can provide a powerful tool for microscopy in the mid-IR, facilitating detection in the near-infrared with a standard CMOS camera.
Our implementation relies on a non-linear interferometer formed between two identical spontaneous parametric down-conversion (SPDC) processes coherently pumped in series. The signal and idler fields emerging from the first crystal are subsequently aligned into the second crystal, erasing any 'which source' information. The strong correlations shared between the signal and idler modes ensure any distinguishing spatial information obtained by the idler is transferred to the signal. Accordingly, a sample illuminated with the mid-IR idler is imaged via the signal with an off-the-shelf CMOS camera. While previous implementations of microscopy with undetected photons [2,3] utilized the momentum correlations between the idler and signal modes for imaging, we use position correlations at the image plane of the crystal to achieve wide-field microscopy. The setup, achieving a resolution of 9 µm, is used to image an unstained histology sample of a mouse heart. This first demonstration of imaging with undetected photons in the image plane is particularly appealing for microscopy implementations, with a comparably simple optical layout accessing high resolutions. These results open a new perspective for potential relevance of quantum imaging techniques in the life sciences.

References

1. M. V. Chekhova and Z.Y. Ou, Adv. Opt. Photon. 8, 104–155 (2016).
2. I. Kviatkovsky, *et al.* Sci. Adv. 6, eabd0264 (2020).
3. A.V. Paterova, *et al.* Sci. Adv. 6, eabd0460 (2020).

Toward quantum 3D imaging devices

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We introduce a new generation of 3D imaging devices based on quantum plenoptic imaging [1]. Position-momentum entanglement and photon number correlations are exploited to provide a scan-free 3D image after post-processing of the collected light intensity signal. We explore the steps toward designing and implementing quantum plenoptic cameras with dramatically improved performances, unattainable in standard plenoptic cameras, such as diffraction-limited resolution, large depth of focus, and ultra-low noise. However, to make these new types of devices attractive to end-users, two main challenges need to be tackled: the reduction of the acquisition times, that for the commercially available high-resolution cameras would be from tens of seconds to a few minutes, and a speed-up in processing the large amount of data that are acquired, in order to retrieve 3D reconstructions or refocused 2D images. To address these challenges, we are employing high-resolution SPAD (single photon avalanche diode) arrays and high-performance low-level programming of ultra-fast electronics [2], combined with compressive sensing and quantum tomography algorithms, with the aim of reducing both the acquisition and the elaboration time by one or possibly two orders of magnitude. Moreover, in order to achieve the quantum limit and further increase the volumetric resolution beyond the Rayleigh diffraction limit, we explore dedicated protocols based on quantum Fisher information [3]. Finally, we discuss how this new generation of quantum plenoptic devices could be exploited in different fields of research, such as 3D microscopy and space imaging.

References

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

Twisted NOON States for Angular Super-Resolution

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Photonic N00N states, i.e., states of light where N photons are in an extremal superposition between two orthogonal states $\frac{1}{\sqrt{2}}(|N,0\rangle + |0,N\rangle)$, have an increased phase-sensitivity in comparison to their classical counterparts [1]. Using this feature in conjunction with the increased angular sensitivity of twisted orbital angular momentum (OAM) states [2], the angular sensitivity and resolution can be scaled to levels not achievable for classical light [3].

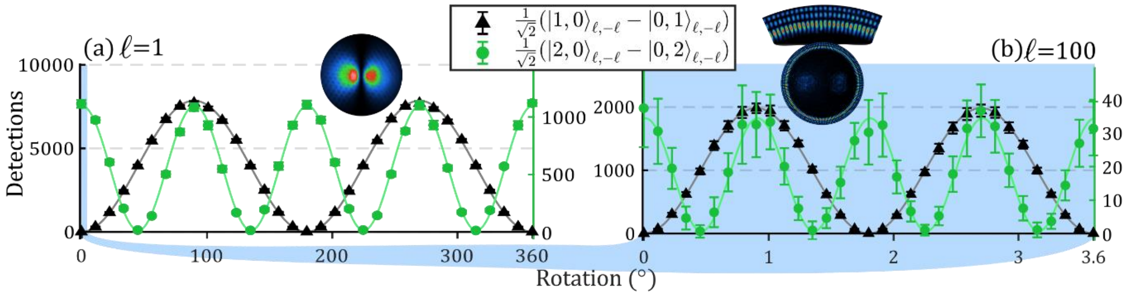

Fig.1: Super-resolution rotation measurements with the OAM values 1 (a), and 100 (b) for single photon (black) and two-photon measurements (green). The single photon superpositions form petal beams that have an OAM-specific rotation symmetry (see insets). Using a two-photon N00N state results in twice the periodicity, hence improving the resolution by a factor of 2.

In this work, we adapt a recently demonstrated method of generating two-photon twisted N00N states [4]. We show that these states are realized through two-photon bunching into transverse-spatial modes and can be used to super-resolve rotations of the transverse beam-structure. To demonstrate the systems capabilities, we measured rotation sensitivities of heralded single photons and two-photon N00N states with OAM values up to 100 (see Fig.1). We further estimated the Fisher information and corresponding angular uncertainty, which scales as $\Delta\varphi \propto \frac{1}{Nl}$ when N is the N00N state photon number and l the amount of OAM [5].
The flexibility of the experimental scheme opens up new possibilities for studying N00N states between arbitrary spatial structures and more general, spatially super-resolved measurements. Additionally, the simplicity of the scheme could be used to overcome the shot-noise limit using the currently available toolbox for spatial mode manipulation.

References

[1] S. Slussarenko, et al., Nature Photonics **11**, 700–703 (2017)
[2] S. M. Barnett, R. Zambrini, Journal of Modern Optics **53**, 613–625 (2006)
[3] V. D'ambrosio, et al., Nature Communications **4**, 1-8 (2013)
[4] M. Hiekkamäki, R. Fickler, Physical Review Letters, **126**, 123601 (2020)
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New applications of twin beams as a quantum tool: from quantum reading to quantum conformance test

M.Genovese,I.Ruo Berchera,G.Ortolano

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Twin beams, an example of photon number correlated states, represent a fundamental tool for developing protocols of quantum metrology-imaging&sensing [1,2].

After a short introduction to this topic we present two recent applications to quantum hypothesis testing.

In quantum reading [3] this advantage is achieved for information retrieval from an optical memory. For this protocol, we describe, theoretically and experimentally, as that quantum advantage is obtained by practical photon-counting measurements combined with a simple maximum-likelihood decision [4], showing that this receiver combined with twin beams is able to outperform any strategy based on statistical mixtures of coherent states for the same mean number of input photons. Our experimental findings demonstrate that quantum entanglement and simple optics are able to enhance the readout of digital data, paving the way to real applications of quantum reading

As a second example we consider both theoretically [5] and experimentally a protocol addressing the task of conformance test with specific attention to the case in which the tested object can be modeled by a pure loss quantum channel. We formulate the problem in the context of quantum hypothesis demonstrating that quantum resources, namely twin beams, and a simple receiver design based on a photon counting measurement are able to outperform any classical strategy in recognizing whether or not a certain quantum channel conforms to a reference one.

References

[1] M.Genovese, J.Opt.18 (2016) 073002.

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[3] S. Pirandola, PRL 106, 090504 (2011).

[4] G.Ortolano, E.Losero, S.Pirandola, M.Genovese, I.Ruo Berchera Sci. Adv. (2021) 7, eabc7796.

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Quantum correlated optical - terahertz biphotons: study and possible applications

G.Kh. Kitaeva[1]

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Extension to the terahertz (THz) frequency range of optical quantum technologies, such as quantum sensing, imaging, spectroscopy, calibration, can be very useful for further development of THz science and may become an urgent task in the near future. By itself, study of statistical parameters of THz radiation at the photon level could give new insights on specific quantum THz states and their interaction with matter. The quantum-correlated pairs of optical and THz photons ("optical - terahertz biphotons"), emitted under spontaneous parametric down-conversion (SPDC) in a strongly non-degenerate regime, are the first examples of non-classical radiation matching the terahertz gap. We study the general properties of such biphotons and the experimental conditions required to get a high degree of correlation between the photons from completely different spectral ranges.

Possible effects caused by the presence of classical thermal field fluctuations and inherent absorption of the non-linear crystal at THz frequencies were investigated using the theoretical approach based on generalized Klyshko-Kirchhoff law [1]. The huge angular diversity of SPDC-generated THz photons was studied both theoretically and experimentally [2]. Comparatively greater progress has been achieved in detecting optical photons, which are emitted at small Stokes shifts, correlate with their THz counterparts, and can provide information on THz properties of matter without direct detection of THz waves [3,4]. However, for a vast majority of attracting applications (ghost imaging without THz cameras, absolute calibration of quantum efficiency of THz detectors, and other tasks), the direct measurement of optical-terahertz correlation function $g^{(2)}$ is important. The solution to this problem is significantly complicated by the lack of current THz receivers capable of operating in the single-photon mode and high-speed coincidence circuits. First results of $g^{(2)}$ measurement using analog readings of an idler THz receiver (a superconducting NbN bolometer) and a signal optical detector (a photo multiple tube) are discussed.

References

[1] G.Kh. Kitaeva, A.A. Leontyev, P.A. Prudkovskii, Physical Review A **101**, 053810 (2020)

[2] G.Kh. Kitaeva, V.V. Kornienko, K.A. Kuznetsov, I.V. Pentin, K.V. Smirnov, Yu.B. Vakhtomin, Optics Letters **44**, 1198 (2019)

[3] K.A. Kuznetsov, E.I. Malkova, R.V. Zakharov, O.V. Tikhonova, G.Kh. Kitaeva, Physical Review A **101**, 053843 (2020)

[4] T.I. Novikova, K.A. Kuznetsov, A.A. Leontyev, G.Kh. Kitaeva, Applied Physics Letters **116**, 264003 (2020)

Broadband diffraction of correlated photons from crystal superlattices

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Sources of broadband quantum correlated photons present a valuable resource for quantum metrology sensing and communication. Here, we demonstrate a comb-like broadband emission of correlated photons from custom-designed nonlinear superlattices on a monolithic LiNb chip. A superlattice is made of regular linear gaps and stacks of periodically-poled domains, where spontaneous parametric down-conversion (SPDC) occurs. The signal and idler photons are generated in the visible and mid-IR, respectively. Interference between wavefunctions of SPDC photons generated in different domains produces a comb-like spectrum. Thus we experimentally demonstrate comb-like broadband diffraction of correlated photons spanning 0.060 µm and 1.4 µm bandwidth at 0.647 µm and 3.0 µm wavelengths.

We demonstrate full control over the comb by tailoring the superlattice parameters (central wavelength, spacing, and bandwidth). Furthermore, we show a superlattice with up to 86 nonlinear elements and exceptional stability, which is impossible to achieve with earlier realizations using individual crystals [1] and nonlinear fibers [2]. Furthermore, our approach is compatible with on-chip LiNb photonics that is gaining significant momentum.

Our superlattice source will enable faster data acquisition via spectral multiplexing for quantum sensing, for example, in schemes based on induced coherence. Furthermore, it is appealing for quantum communication and key distribution due to easier targeted frequency multiplexing. Our concept offers an exciting analogy between optical diffraction in quantum and classical optics from a fundamental perspective.

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Quantum Interference Recovered by Broadband Amplitude Measurement in an Unbalanced SU(1,1) Interferometer

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It is known that quantum interference can disappear with the mere possibility of distinguishability without actually performing the act [1]. We create such distinguishability in an unbalanced SU(1,1) interferometer and indeed observe no interference in the direct photodetection of the outputs (see Fig. 1). On the other hand, such distinguishability can be erased with a projective measurement [2]. In this talk, we report a method of homodyne detection that can also recover interference effect. We find that it is the indistinguishability in amplitude measurement that leads to the recovery of interference and the quantum nature of homodyne detection, and the detector's slow response time both play an essential role.

The unbalanced interferometers have practical implication in optical sensing where one arm of the SU(1,1) interferometer usually goes through a long sample [3]. If interference exists in the unbalanced case, it is not necessary to introduce path compensation in the other arm, creating flexibility and convenience in quantum sensing applications.

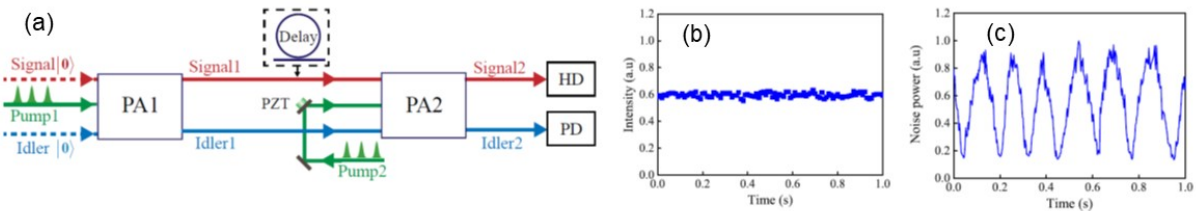

Fig. 1 Observation of quantum interference by using piezoelectric transducer (PZT) to scan the phase in an unbalanced SU(1,1) interferometer. (a) Schematics for the SU(1,1) interferometer with one-pulse delay in signal channel. (b) Disappearance of interference in direct power detection (PD) and (c) recovery of interference fringe in homodyne detection (HD) whose local oscillator is a short pulse train with broadband spectrum.

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Quantum Fourier-transform Infrared Spectroscopy

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Fourier-transform infrared (FTIR) spectroscopy is a well-established analytic technique due to its ability to combine high spectral coverage and spectral resolution. An important limitation to the achievable sensitivity of the devices are the mid-infrared detectors, which achieve significantly lower specific detectivities than detectors for visible or near-infrared light. Nonlinear interferometers using correlated photon pairs have demonstrated mid-infrared spectroscopy using visible or near-infrared light detection. In our work, we demonstrate a realization of a nonlinear interferometer in close analogy to a classical Fourier-transform spectrometer, which allows for broadband spectral coverage and sub-wavenumber spectral resolution [1,2]. Our contribution describes practical aspects of Fourier-transform metrology with nonlinear interferometers and characterizes the limitations considering the spectral resolution and sensitivity.

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Quantum Assisted Optical Telescopes

A.Nomerotski, P.Stankus, A.Slosar, S.Vintskevich, N.Bao

Observations using interferometers provide sensitivity to features of images on angular scales much smaller than any single telescope due to large interferometric baselines. Present-day optical interferometers are essentially classical, interfering single photons with themselves. However, there is a new wave of interest in interferometry using multiple photons, whose mechanisms are inherently quantum mechanical, which offer the prospects increased baselines and finer resolutions among other advantages. We will discuss recent ideas for quantum-assisted interferometry using the resource of entangled pairs, and specifically a two-photon amplitude technique aimed at improved precision in dynamic astrometry.

It was pointed out by Gottesman, Jennewein and Croke in 2012 that optical interferometer baselines could be extended, without an optical connecting path, if a supply of entangled Bell states between the two stations could be provided. If these states could then be interfered locally at each station with an astronomical photon that has impinged on both stations, the outcomes at the two stations would be correlated in a way that is sensitive to the phase difference in the two paths of the photon. Equivalently, this can be seen as using a Bell state measurement at one station to teleport the state of that station's astronomical photon to the other station, and interfering it with its counterpart there.

In the presentation we will discuss several quantum-assisted schemes of two-photon interferometry extending the original ideas which could enable practically arbitrarily large synthesized apertures, opening completely new windows into astrophysical phenomena. We also describe first results of several proof-of-principle experiments, showcasing the observational methods assisted by entanglement of photons.

Heralded spectroscopy reveals exciton-exciton correlations in single colloidal nanocrystals

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Multiply-excited states in semiconductor nanocrystals feature intriguing physics and play a crucial role in nanocrystal-based technologies. While photo-luminescence provides a natural probe to investigate these states, room temperature single-particle spectroscopy of their emission has so far proved elusive due to the temporal and spectral overlap with emission from the singly excited and charged states. In this work, we perform heralded spectroscopy of single quantum dots by incorporating the rapidly developing technology of single-photon avalanche diode arrays [1] in a spectrometer setup. This allows us to directly observe the biexciton-exciton emission cascade and to measure the biexciton binding energy of single nanocrystals at room temperature, as shown in Fig. 1, even though it is well below the scale of thermal broadening of the transitions due to finite temperature and that of spectral diffusion, the shift of the transition energy due to fluctuating electric fields. Single-particle heralded spectroscopy enables us to identify correlations of the biexciton binding energy with both charge-carrier confinement and fluctuations of the local electrostatic potential, which are masked in ensemble measurements, and to overcome artifacts due to inhomogeneous broadening [2]. Time-resolved spectrometry, as demonstrated here, has the potential of greatly extending our understanding of charge carrier dynamics in multielectron systems and of parallelization of quantum optics protocols.

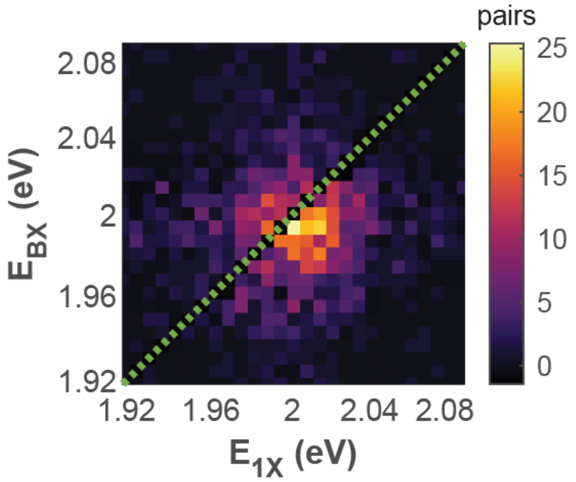

Fig. 1: Correlation between the energy of the first emitted photon (vertical axis) and the second emitted photon (horizontal axis) from a single CdSe/CdS/ZnS quantum dot. The center of mass is below the diagonal, indicating an attractive interaction.

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Unbalanced Interferometers for Sensing

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Interferometry has been used widely in sensing application. However, the technique is limited by the finite coherence time of the light sources when the interference paths are not balanced. Higher-order interference effects involve intensity correlations between multiple detectors and may have the advantage over the traditional second-order interference effects that are exhibited in only one detector. We discuss various scenarios in fourth-order interference with unbalanced delays in different paths. We find that in some cases, interference effect persists even when the delays are much larger than the coherence time of the sources. We apply the above results to an unbalanced Hong-Ou-Mandel interferometer (HOMI) with a train of ultra-short pulses and use it to measure the dispersion of a long fiber (200m). Compared to traditional methods, the current method is not limited by the coherence length of the laser and is insensitive to phase fluctuations in fibers. A brief discussion on unbalanced SU(1,1) interferometers will also be presented.

Near-field Subdiffraction Resolution Quantum Imaging with Undetected Photons

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Quantum imaging with undetected photons allows for imaging an object by detecting photons that never interacted with it, using the correlation between photon pairs generated in the process of spontaneous parametric down conversion (SPDC) [1]. In such imaging schemes, the object's optical properties at the idler wavelength such as its absorption profile, can be inferred by only imaging the signal photons. Thus, one can image in challenging spectral ranges, such as illuminating the object in the mid-IR, using detectors in the visible. In this scheme, the resolution is fundamentally diffraction-limited to the longest wavelength generated in the SPDC process [2].

We will show that one can go beyond this diffraction limit through transferring the near-field information of the idler into propagating modes of the signal that can be detected in the far field. In this scenario, the resolution of imaging the object at idler wavelength is determined by the detected smaller signal wavelength. This is done by placing the object in the near-field of a subwavelength thin SPDC source to affect the pair generation by directly changing the optical properties of the source at the idler frequency as shown in Fig. 1. This allows transferring near-field information, into propagating signal modes. More specifically, we show that a near-field and spatially localized change in the optical density of states (DOS) at the idler frequency can be mapped to the spatial properties of the propagating signal photons that can be collected using a far-field optical imaging setup, which now contains the subwavelength information of the object at the idler frequency.

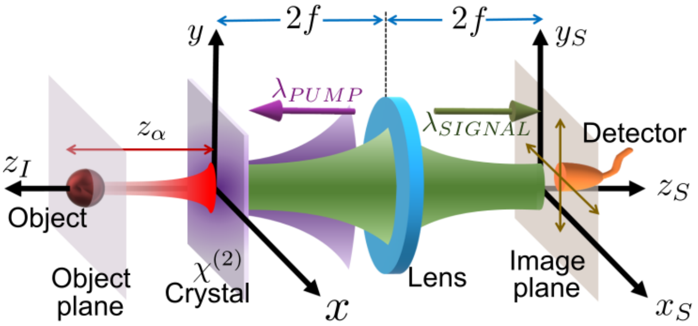

Fig. 1 Proposed scheme. Here a point-like object interacts with the idler near-field by placing it a subwavelength distance z_α from an ultrathin nonlinear source. The signal photons are collected with a far-field imaging system.

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Quantum metrology of two-photon absorption

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We will present an analysis of the achievable sensitivity for estimating the two-photon absorption (TPA) cross-section [1]. We find that there is no fundamental limit for the precision achievable with squeezed states in the limit of very small cross sections. Considering the most relevant measurement strategies---namely photon counting and quadrature measurements---we determine the quantum advantage provided by squeezed states as compared to coherent states. We find that squeezed states outperform the precision achievable by coherent states when performing quadrature measurements, which provide improved scaling of the Fisher information with respect to the mean photon number. Due to the interplay of the incoherent nature and the nonlinearity of the TPA process, unusual scaling can also be obtained with coherent states, which feature a cubic scaling in both quadrature and photon-counting measurements.

In the second part of the talk, we will then analyze the influence of single-photon losses on these optimal sensitivities and simulate TPA measurements in nonlinear interferometers.

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Squeezed light – now exploited by all gravitational-wave observatories

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Light with squeezed quantum uncertainty allows for the sensitivity improvement of laser interferometers. Since 2010, the gravitational-wave (GW) detector *GEO600* has been using squeezed light in all of its searches for GWs [1]. The successful sensitivity improvement triggered the implementation of squeezed light sources also in *Advanced LIGO* and *Advanced Virgo*. On April 1st, 2019 these observatories started their third observational run. Since then they have been detecting more than one GW event per week. An increased event rate of up to 50% is due to the exploitation of squeezed states of light [2,3]. Squeezed light is fully described by quantum theory, however, observations on squeezed light represent physics that is not self-evident. I present a clear description of why a squeezed photon counting statistic is rather remarkable [4].

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Spatial properties of entangled two-photon absorption

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Two-photon absorption is a well-studied process, well-known for its quadratic dependence of the absorption rate on the input flux, and thus for its inefficiency, requiring high power laser pulses to compensate it. It thus, automatically excludes samples with the low damage thresholds from consideration.

The recent concept of entangled two-photon absorption (ETPA) predicts a linear dependence of its rate on the pairs flux in the low-power regime [1, 2], and provides a tool to overcome this obstacle. Previous studies demonstrated this linear dependence on the flux in an assumption of constant beam waist size, varying only the excitation pair rate. It leaves unanswered a fundamental question – whether ETPA acts spatially like a single photon process, or it scales similar to classical two-photon absorption?

To answer this question we performed a Z-scan measurement on a Rhodamine 6G film (Fig. 1) with SPDC pairs as an excitation, observing the ETPA-induced fluorescence. This lets us demonstrate, first to our knowledge, ETPA dependence on the beam waist size.

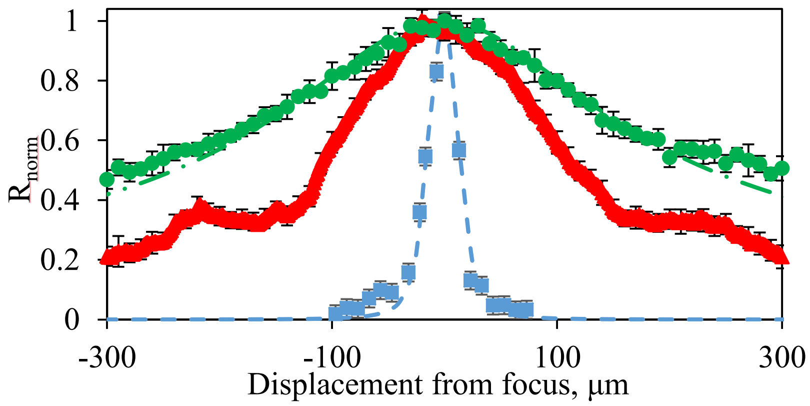

Fig. 1. Normalized dependence of detected fluorescence count rate as a function of translation stage position relative to inducing fluorescence SPDC (red triangles), 532 nm continuous-wave laser (green circles) and 1064 nm continuous-wave laser (blue squares) beam focuses.

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Efficient entangled photon sources and their applications

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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. Entangled photons are the key resource for these applications. In this talk, we will report our recent progresses on the development of novel quantum entangled-photon sources and application to quantum sensing.

First, we report the efficient generation of ultra-broadband parametric fluorescence using chirped quasi-phase-matched (QPM) waveguide devices [1]. Broadband frequency-entangled photons are useful resource for quantum technologies, for example, quantum optical coherence tomography (QOCT) and infrared quantum absorption spectroscopy (IRQAS). For a broader bandwidth, chirping of the poling periods of a QPM device has proven promising. Here we report a highly efficient photon pair source using chirped QPM devices with a ridge waveguide structure. For a 6.7% chirped device, we observed 325 nm in FWHM (428 nm in base-to-base) with the estimated efficiency of 1.2×10^6 pairs/s·μW, which is about 600 times larger than that observed for a bulk-type chirped QPM device.

Next we report the broadband generation of photon-pairs using CMOS compatible ring resonators [2, 3]. We investigated the photons generated via spontaneous four wave mixing (SFWM) in a high-index contrast doped glass (HICDG) ring resonator and a SiN ring resonator. For the HICDG resonator, we observed that the generated signal and idler photons are correlated over 59 frequency modes, corresponding to a bandwidth of 23.6 nm. For the SiN ring resonator, we confirmed photon pair generation correlated in frequency over a 51 nm.

We will also discuss our recent work on the direct and efficient verification of entanglement between two multimode–multiphoton systems [4]. Entangled states with multiple photons in multiple modes are attracting attention, however, the efficiency of entanglement verification is strictly limited since the required resources for quantum state tomography increase exponentially as the number of photons/modes increases. We show that using just two sets of classical correlation tables with and without a discrete Fourier transformation, the entanglement of the two systems is verified. We will also briefly introduce our recent work on the quantum Fourier-transform infrared (QFTIR) spectroscopy for complex transmittance measurements [5].

These works were supported in part by JST-CREST (JPMJCR1674), MEXT Q-LEAP project (JPMXS0118067634), and Grant-in-Aid from JSPS (21H04444 and 26220712).

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Towards Practical Quantum Optical Coherence Tomography

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Optical Coherence Tomography (QOCT) was proposed as a technique for the determination of the internal morphology of semi-transparent samples, e.g. biological, with some clear advantages over analogous techniques based on classical physics. QOCT is based on the use of photon pairs with quantum entanglement properties. It has been shown that an even-order dispersion cancellation phenomenon occurs and that the resolution is enhanced by a factor of two, for a given bandwidth, compared to an equivalent classical system. However, considering a number of technical difficulties, including low photon pair fluxes, QOCT has not become a practical technique usable, for example, in clinical settings. Here we present a series of advances, coming from our research group, aimed at the practical implementation of QOCT. In particular, first, we demonstrate a novel technique for the suppression of cross interference effects. Secondly, we demonstrate a demonstration of full-field QOCT. Thirdly, we demonstrate a frequency-resolved QOCT apparatus which eliminates the need for axial scanning of the sample.

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Quantum Light for Sensing of Organic and Biological Materials

Juan P. Villabona-Monsalve, **C. Gunthardt, O. Varnavski, and T. Goodson III**
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The last couple of decades have witnessed the emergence of entangled photons (EP) to probe quantum mechanics processes in atomic and molecular systems. In particular, EP pairs have been used as the excitation source of two-photon absorption (TPA). In the entangled TPA (ETPA) technique, entangled photon pairs (in time and frequency domain) are absorbed simultaneously by a chromophore. Due to entanglement, the absorbed photon rate depends linearly on the input photon flux; and this dependence is quadratic for classical TPA. One additional advantage of ETPA is observing the process at an ultralow light intensity, around six orders of magnitude less than that in the classical experiments. We have utilized this approach in organic and biological molecular systems. We identified highly ETPA-efficient endogenous flavins probes and demonstrated their ability to be used in a real bioenvironment at extremely low excitation light intensity. Flavoproteins are involved in several relevant biochemistry processes. Free and protein-embedded flavins were studied in aqueous solutions. Our results illustrated that flavins are highly sensitive to ETPA, showing a relatively large response compared with classical light-induced TPA.[1] EP pairs exhibit strong nonclassical frequency and time correlations simultaneously, which allow them to perform non-linear spectroscopy and microscopy in new ways compared to classical means. In this talk, we will also explore ETPA as an analytical technique that exploits the nonlinear absorption of quantum light.[1, 2] We have successfully created an entangled two-photon (E2P) quantum microscope that showed enhanced sensitivity compared to the classical approach.[3] This homebuilt scanning microscope has been used to collect fluorescence images of organic thin films using classical and E2P excitation. ETPA induced fluorescence was detected using around six orders of magnitude fewer photons than required to observe TPA-induced fluorescence using classical light. We have also exploited photon quantum correlations of EP to study molecular properties by utilizing a combination of Hong–Ou–Mandel (HOM) interferometry and molecular spectroscopy.[4] Our experiments can be used to analyze a wide variety of chromophores of chemical and biological significance.

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Quantum imaging with incoherently scattered light

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For more than 100 years, X-rays have been used in crystallography to determine the structure of crystals and molecules via coherent diffraction imaging (CDI). With the advent of accelerator-driven free-electron lasers (FEL) new avenues for high-resolution structure determination are explored which go even beyond conventional X-ray crystallography methods [1–3]. However, the mentioned techniques rely on the coherent scattering of light where incoherence due to fluorescence emission or wavefront distortion is considered as detrimental. Here we show that methods from quantum imaging, i.e., exploiting higher order photon correlations, can be used to image arrangement of sources that scatter incoherent X-ray radiation, e.g., atoms in crystals or molecules emitting X-ray fluorescence photons [4–8]. We discuss a number of properties of incoherent diffraction imaging (IDI) that are conceptually superior to those of conventional CDI and point out that current FELs are ideally suited for the implementation of the approach [7]. We also present recent experiments where IDI has been implemented in the optical domain using fluorescence photons scattered by laser-cooled ion crystals [9,10].

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Abstracts of Posters

(in alphabetical order)

An optomechanical force sensor with feedback-controlled in-loop light

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Among quantum control techniques, measurement-based feedback allows efficient control of optomechanical systems and quantum-enhanced sensing. Here, we present an optomechanical force sensor capable of surpassing the standard quantum limit and ensuring efficient force sensing in a broad frequency band. Operation in the resolved-sideband regime pushes the sensor beyond the standard quantum limit. At the same time, the addition of a feedback loop on the light used to read out the mechanical motion amplifies the mechanical signal. This combination results in a stronger signal inside the sensor and a larger bandwidth of the transduced force. Optomechanical force sensors enjoy increasing attention for applications ranging from biology and medicine to gravitational wave detection and tests of fundamental physics. We provide a clear avenue for improving the sensitivity and bandwidth of these devices without the need to hybridize them with other quantum systems or introduce nonlinearities that are often needed to improve the performance of quantum force sensors.

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Development and characterization of a highly non-degenerate polarization-entangled Sagnac photon pair source

Vira R. Besaga[1], Andres Vega[1], Valerio Gili[1], Francisco Páez Larios[1], Emma Brambila-Tamayo[2], Thomas Pertsch[1,2], Markus Gräfe[2] and Frank Setzpfandt[1]

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The core element of a quantum instrument intended for the non-local quantum imaging and metrology is the source of the entangled photon pairs. The mutual entanglement of the generated photons underlies the principles of the non-local access to the photon-related parameters and is employed in various non-classical imaging approaches, e.g. in ghost imaging [1]. Especially promising solutions relate to the highly non-degenerate entangled photon pairs aiming at entering the near- and infrared spectral range for the sensing/imaging purposes while still utilizing the high-efficiency detectors available for the visible range. Even more comprehensive metrology and characterization of the samples under study can be obtained providing the polarization properties of the specimen become distinguished and/or spatially resolved concurrently with the field intensity distribution. On the path towards reproducible and highly sensitive quantum measurements, the source should exhibit a high level of stability and photon pair generation, which, in their turn, draw the trade-off with the complexity of single optical components and the instrument as a whole. Here we discuss the practical challenges and possible solutions that accompany the construction and characterization of such a highly non-degenerate polarization-entangled photon pair source on example of the Sagnac-based geometry with a single nonlinear crystal. We focus on the employment of the type 0 phase matched periodically poled KTP bulk crystal pumped at 420 nm by the continuous wave frequency-doubled Ti:Sa laser. The photons generated through the process of spontaneous parametric down-conversion correspond to 620 and 1302 nm. Taking into account the loop geometry of the photon-pair source and the significant spectral separation between the generated photons, we regard the selection of the components applicable for such a source operation, alignment and operation tricks, as well as the characterization approaches.

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Shaping photon pair correlations with an SLM

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Detecting correlations between photon pairs is an essential technique for imaging regimes that aim to exploit their entanglement. Methods have been developed to use electron multiplying CCD (EMCCD) cameras to measure these correlations, and in fact the full joint probability distribution of the photon pair source can be computed. We show that the structure of the correlations can in fact be shaped using a SLM in a manner analogous to classical beam shaping. Finally, we aim to extend this by using multiple SLMs to manipulate the structure of the JPD itself.

Revealing and concealing entanglement with noninertial motion

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Photon interference and bunching are widely studied quantum effects that have also been proposed for high-precision measurements. We construct and use a theoretical description of photon interferometry on rotating platforms, specifically exploring the relation between noninertial motion, relativity, and quantum mechanics. We propose an experiment testing these relations where photon entanglement can be revealed or concealed solely by controlling the rotational motion of an interferometer[1].

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Multidimensional sensing of hot Rb vapor with squeezed light

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Four-wave mixing (FWM) of optical fields has been extensively used in quantum information processing, sensing, and memories. It also forms a basis for nonlinear spectroscopies transient grating, stimulated Raman and photon echo where phase matching is used to select desired components of the third-order response. Here we report an experimental study of the 2D quantum noise spectra of the intensity difference of the squeezed beams generated by FWM in hot Rb vapor [1]. The measurement reveals details of the third order nonlinear susceptibility dressed by the strong pump field including the AC Stark effect with higher spectral resolution compared to classical measurements of probe and conjugate beam intensities. Quantum signals, unlike the classical counterparts, are robust to external noise. We demonstrate how quantum correlations of squeezed light can be applied as a spectroscopic tool [2].

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Quantum Rangefinding

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Rangefinding has a broad field of applications in the defence and public sectors. However, state of the art rangefinders rely on few photons being reflected from a target which originally stem from a bright laser beam aimed at the target. The brightness and unique spectral signature of lasers make them detectable for the target.

Here we present our Quantum Rangefinder [1], a rangefinder using the single photons from a spontaneous parametric down conversion (SPDC) source, which enables efficient camouflaging against background light. Inspired by Quantum Illumination we use (spectral) entanglement, i.e. one mode of a two-mode squeezed state, to illuminate a object at a distance with a perfectly mixed/thermal state. This protocol enables us to extract position information about an object without revealing ourselves, since the illumination source is indistinguishable from background light

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Quantum Holography with Undetected Light

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Induced coherence-based experiments have recently gained the attention of the scientific community. Firstly introduced by Mandel's group[1], this effect shows the interaction of a photon pair produced by spontaneous parametric down-conversion (SPDC) wherein a which-path indistinguishable photon induces coherence on its partner. Moreover, the quasi-phase matching condition in SPDC allows us to select the photons wavelengths far apart in the electromagnetic spectrum. Therefore, experiments based on this effect enable us to probe samples at wavelengths with detection constraints while a more favorable wavelength is detected[2]. For example, recent experiments have shown a probing wavelength at the mid-, far-infrared, or terahertz range, while its detected partner photon is located at the visible range[3]. Here, we introduce a novel application based on this effect.

Digital phase-shift holography[4] is an interferometric technique that allows a simultaneous extraction of phase and transmission information from a sample. Taking this technique to the quantum domain, we can perform quantum holography with light that remains undetected[5]. Thus, we extract phase and transmission of an object without detecting the light that illuminates the sample. In this contribution, we addressed the performance of our technique in terms of transmission and phase precision retrieval, spatial resolution, acquisition time, and the number of frames needed to reconstruct an image.

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Scanning Quantum Microscopy

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Ghost Imaging is a fascinating technique that exploits two-photon correlations [1]. It has been investigated for more than two decades, with the demonstration of remarkable results such as 3D imaging, ranging, two-colour imaging, and enhanced signal-to-noise ratio. The last two features in particular, have been demonstrated in the quantum regime, enabled by the position/momentum correlations of photon pairs generated through Spontaneous Parametric Down-Conversion (SPDC). So far, practical application of this technique have been limited in terms of acquisition time by raster scanning, or the slow electronics of ICCD cameras, and in terms of resolution by the finite width of the Joint Spectral Amplitude (JSA) of SPDC sources [2]. In our approach, we demonstrate heralded imaging with a scanning microscope (SM). Correlated photon pairs are generated through type-0 SPDC from a Ti-diffused LiNbO waveguide that delivers photons in the spectral range 1000 nm – 2400 nm [3]. The photon pairs then get split, and while the idler photons are directly detected with a superconducting nanowire single photon detector (SNSPD), the signal photons are coupled to the LSM by means of a free-space periscope. Two galvo mirrors allow to scan the sample in two dimensions, while reflected photons get collected through the same objective and sent along the same input path, from which they then get separated with a polarizing beam splitter and a Faraday rotator. Finally, the signal photons are detected with a 2nd SNSPD. Time tags are registered with a TDC and correlated images are reconstructed together with trigger signals from the LSM scanner. We first tested contrast and resolution performances on a 2D Silver-on-glass grating with different scanning parameters and objectives, then reconstructed the sample transmittance through Klyshko efficiencies [4], and finally performed quantum correlated imaging of onion cells. Our results pave the way towards practical applications of Ghost Imaging in the investigation of biological samples.

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Evaluation of incoherent seeding on the performance of nonlinear interferometers

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In the past few years, sensing and imaging with undetected photons, an effect that is based on the nonlinear interference of biphotons generated in nonlinear crystals, has undergone a huge development and its potential has been demonstrated for various spectral regions. However, if the idler photons have very small photon energy like for example in the terahertz frequency range, there exists thermal idler radiation at room temperature [1]. In order to investigate this temperature effect, a nonlinear Mach-Zehnder interferometer based on the original setup of Lemos et al. [2] was modified and incoherently seeded to evaluate the seeding's influence on the performance of nonlinear interferometers. Here, due to spontaneous parametric down-conversion and difference frequency generation with the incoherent seed a 532 nm pump laser generate signal and idler photons at 810 nm and 1550 nm, respectively. While the idler radiation interacts with a sample solely the interference of the signal photons, which are generated in one of the two nonlinear crystals, are detected with a scientific CMOS camera. As long as both the signal and the idler radiation of the crystals overlap, the sample's information is transferred from the idler photons to the frequency range of the signal radiation. Due to more sophisticated imaging technology the signal radiation is much easier to detect. With the additional influence of the incoherent idler seeding, the measured count rate increases by a factor of around 70. Additionally, the visibility of the signal photon interference increases from around 70% without seeding to more than 90% with the seed as well [3]. These findings might be useful to enhance the sensitivity of applications in spectral regions with low count rate and bad visibility.

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Towards low-cost nonlinear interferometry

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Sensing and imaging with undetected photons has been demonstrated in different experiments and spectral ranges over the last few years. In order to make the step from the lab to application-oriented usage, cheaper and more compact components must be used compared to typical laboratory devices. Here, we show a first approach by replacing the two most expensive components using a cheaper camera and laser source. The experimental setup is based on that presented by Lemos et al. in [1]. Two nonlinear crystals arranged in a Mach-Zehnder-interferometer are pumped with 532nm laser light creating correlated pairs of photons with different wavelengths by spontaneous parametric down conversion. Only the idler photons at 1550nm interact with an object, yet the signal photons at 810nm carry the information of the object as well and are detected with a CMOS camera. As lab equipment, we use a “Quantalux” camera by Thorlabs and a “Cobolt Samba” laser by Hübner Photonics and the alternative components are a “DMM 37UX273-ML” board camera by The Imaging Source and a “DJ532-40” laser diode by Thorlabs. These components are more than ten times cheaper and much more compact than the previously mentioned ones. Although the laser diode with a maximum power of 40mW has significantly less laser power than the solid-state laser with a maximum of 1500mW, the necessary exposure time of the camera can be kept comparable to the lab setup by applying an external seed. The quantum efficiency at the signal wavelength of 810nm of the Quantalux camera is about 32%, whereas the DMM 37UX273-ML camera has a quantum efficiency of about 25%. This experiment shows that it is possible to realize a quantum sensing experiment using also lower priced components. Using more cost efficient components could help make such a setup more commercially competitive in the future.

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Imaging with undetected photons in MIR with large-aperture nonlinear crystals

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Spontaneous parametric down-conversion (SPDC) can produce pairs of entangled photons with very different wavelengths. For applications like optical spectroscopy and imaging, this offers the possibility of separating the spectral range of interaction with the sample from the spectral range of photon detection. Lemos et al.[1] have shown the feasibility of what has been named quantum imaging with undetected photons. This way, highly developed silicon photo detectors, that show a peak sensitivity in the visible (VIS) to near infrared (NIR) spectral range, can be used for optical imaging of samples in exotic wavelength ranges. Within the frame of the Fraunhofer lighthouse project QUILT we aim to extend this approach to new wavelength ranges, in our case to the mid-infrared.

To achieve this, we investigate the imaging performance of a nonlinear Mach-Zehnder interferometer with two SPDC sources. Imaging with undetected photons has been achieved, where the illumination wavelength was 3.4 µm.
The resolution and the visibility are under on-going investigation. Fundamental limitations are set by crystal apertures as well as crystal length and absorption. With periodically poled nonlinear crystals of large aperture not yet fully developed, our approach involves using bulk material for large apertures.

With a maximum pump beam diameter of 8 mm, we demonstrated a resolution of down to 70 µm with a field of view of 1490 µm which equates to roughly 450 resolvable 2D-elements.

Improvements to the setup could possibly be facilitated by larger pump powers for increased SNR on the camera and a revised mechanical design for increased mechanical stability.

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Broadband Mid-IR Spectroscopy with Near-IR Grating Spectrometers

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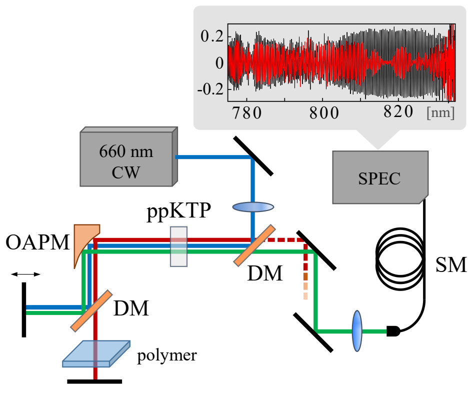
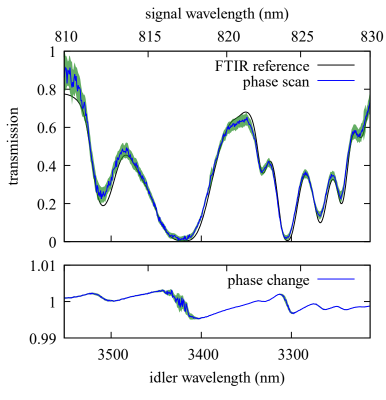
For the identification and analysis of many materials, including gases, polymers or tissue samples mid-infrared (mid-IR) spectroscopy is an indispensable tool, because their molecular rotational-vibrational absorption features between 2.5 to 10 µm result in distinctive fingerprints used for composition determination. In contrast to spectroscopy in the visible wavelength region, where grating spectrometers are commonly used, Fourier transform infrared spectroscopy (FTIR) is the favoured approach for implementing spectroscopy in the mid-IR. This is a consequence of the fact that at mid-IR wavelengths, detector noise is the dominant limitation, which Fourier-transform spectroscopy can mitigate via its Fellgett advantage [1]. However, the resulting instrumentation remains complex and bulky, requires moving parts and often has to implement cryogenically-cooled detection.

Here we present a method that does not require mid-IR detectors, but rather leverages the benefits of fast, cost-effective near-IR Si-CCD based grating spectrometers. We do so by accessing the mid-IR range using broadband and widely non-degenerate photon pairs (signal: 780-830 nm; idler: 3.2-4.3 µm) created in a custom designed ppKTP crystal [2] inside a nonlinear interferometer [3]. Our method builds upon the first demonstration of nonlinear interferometry for spectroscopy [4], and its subsequent improvements [5, 6], for which resolution, spectral bandwidth or acquisition times have remained key limitations. Overcoming those limitations, our setup (Fig. a) can realise two complementary measurement techniques either prioritising measurement speed or resolution. Firstly, with a single shot measurement over 1 s, we can acquire mid-IR absorption spectra with a resolution of 9 cm^{-1}, enabling the identification of polymers such as polystyrene (Fig. b). Secondly, we use a phase-scanning technique to acquire several spectra at equidistant interferometric displacements. With a total acquisition time of around 100 s we can reconstruct the visibility (and thus the absorption of the sample) for each spectral bin of the spectrometer resulting in a resolution of 1.5 cm^{-1} across the full range of 3.2-4.3 µm. Here, the resolution—limited only by the non-optimised grating spectrometer—is suitable also for trace gas sensing such as atmospheric CO_2.

Further improvements to brightness of the source and the resolution of the spectrometer will further increase the competitiveness of our proof-of-concept demonstration. Owing to its existing simplicity, robustness and cost-effectiveness, we see the potential for a wider adoption of nonlinear interferometry schemes in the field of mid-IR spectroscopy for applications such as polymer analysis or gas sensing.



(a) Setup scheme



(b) Polymer transmission and phase change

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Fundamental Limits on Estimation of Molecular Parameters Using Entangled Photon Spectroscopy

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Nonlinear spectroscopy using entangled photons has been shown to offer a number of apparent advantages over classical light, including increased selectivity in exciting transitions[1], enhanced signal-to-noise ratio of detected signal[2], as well as a larger set of control parameters (such as entanglement time). In this poster, I will recast the basic spectroscopic question of how much information about the matter system one can extract from the detected state of quantized light as that of a quantum estimation problem. By evaluating the quantum and classical Fisher matrices (with respect to the parameters of interest of the matter system) of the output states of light, we can estimate the optimal input field states as well as the detection schemes for the inference problem. I will illustrate this in the context of the linear biphoton spectroscopic probe[3] of a coupled dimer, where one of the members of an entangled photon pair (resulting from a type-II parametric down-conversion (PDC) process) couples with the matter system, and is detected in coincidence with the other photon. Under the influence of various models of the bath that couples to the matter system, I will show that entanglement of the input probe state of light plays a role in setting these fundamental bounds. I will also examine the analogous problem with other quantum states of light, as well as classical fields, to demonstrate the relative usefulness of the various probes in our estimation paradigm.

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Integrated nonlinear quantum interferometer with parity-time symmetry

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Nonlinear interferometry can enable efficient sensing and imaging applications at few-photon levels in technologically important infrared wavelength ranges [1,2]. Integrated photonic platforms may further expand the utility of such interferometers by tailoring light-matter interactions. In this work, we propose a new principle of enhancing sensing and spectroscopy with a nonlinear quantum interferometer by drawing on the concept of parity-time symmetry [3]. We propose a system where photon-pairs are generated through spontaneous parametric down-conversion (SPDC) at the beginning and the end of a nonlinear waveguide, with the periodic poling optimized for maximum efficiency of nondegenerate process where the idler photon wavelength is much larger than that of the signal photon. The poling is intentionally absent in the central section, where a second lossy waveguide is evanescently coupled to the first waveguide, thereby forming a parity-time (PT) symmetric system. The coupling between the two waveguides of PT coupler is chosen such that only the longer-wavelength idler photons can tunnel back and forth between the waveguides and thus can sense the optical loss of the second waveguide. The signal and pump photons always remain confined to the first lossless waveguide. Finally, to perform the sensing only the signal photon flux is detected, which is governed by the interference between the photon pairs. We show that the resulting signal intensity can reveal information about the loss in the second waveguide. Importantly, we identify a new phenomenon of sharp transition at a critical loss value, where the interference fringes are suddenly shifted by half a period. This opens new possibilities for sensing weak perturbations in the second waveguide across broad spectral regions.

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Broadband Fourier-transform infrared spectroscopy with visible Light

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With nonlinear interferometers, broadband mid-infrared spectroscopy using only near-infrared detection becomes possible. In this work, we use the correlation of the signal and idler photon pairs emitted by SPDC in a periodically poled lithium niobate crystal. With that we design and realize a nonlinear interferometer in Michelson geometry. The measurement principle is analogue to that of a classical FTIR spectrometer - with the difference, that the spectral information from the mid-infrared (idler photons) is gained by detecting only in the near infrared (signal photons). This allows us to do FTIR spectroscopy with sub-wavenumber spectral resolution and more than 1000 cm^{-1} spectral bandwidth in the mid-infrared with a single-pixel Silicon-based detector. Therefore, the measurement principle is of huge interest for applications such as spectroscopic gas analysis.

Terahertz material characterization with visible photons

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New quantum-inspired methods of sensing [1] and imaging [2] have recently become popular schemes to measure optical properties of samples in the infrared spectral range with only visible photons being detected. These principles are based on nonlinear interferometers in which pairs of correlated photons called signal and idler are generated by pumping nonlinear crystals. If signal and idler photons are processed the right way, an interference between the signal as well as idler photons from different sources can be observed. The interference of each individual part of the spectrum depends not only on itself, but also on the other. A change of the optical properties in one of the spectral ranges therefore has a direct influence on the interference in the other spectral range. This is particularly interesting for a large spectral separation between signal and idler photons, since sample interaction and detection can then be realized in different spectral ranges. Especially, applications in the terahertz range still suffer from the technically demanding detection of this radiation. Either coherent time domain spectroscopy or continuous wave detection with photomixers is used requiring expensive laser systems just to avoid the complexity of cooled detectors. We report on the extension of this new quantum-inspired detection principle into the terahertz frequency range, where the sample interacts with terahertz photons, while only correlated visible signal photons are detected [3,4].

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Advances in Quantum Metrology for Precise Measurements

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Quantum metrology overcomes standard precision limits and has the potential to play a key role in quantum sensing. Conventional bounds to measurement precision such as the shot-noise limit are not as fundamental as the Heisenberg limits and can be beaten with quantum strategies that employ 'quantum tricks' such as squeezing and entanglement. Bipartite entangled quantum states with positive partial transpose (PPT), are usually considered to be too weakly entangled for applications. In the very 1st paper related to the usefulness of PPT states in metrology, the respected authors provided a specific strategy, Entanglement assisted strategy (EAS), for a family of PPT states claiming to have the highest possible accuracy, obtained from convex optimization. However, we, in our article, provided a modified strategy named "sequential" Ancilla assisted strategy (SAAS). We, through detailed calculation and plots, showed It can outperform the previous strategy for the same family of PPT states and can be applied to any family of states. Further, we reiterate the fact that sequential strategies are completely distinct from the repetition of an experiment multiple times. If we add repetitions to the experiment the Quantum Fisher Information (QFI) scales linearly in the number of repetitions, the concept of having sequences in both "EAS" and Ancilla assisted strategy can quadratically increase the QFI in the number of sequences and thus can scale in total O(n^3) (n=number of sequences as well as repetitions) and provide a greater advantage in metrology and sensing e. g. in magnetometry, gravitational wave detection, etc. Furthermore, we investigate the role of noise.

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A wavelength variable visible-infrared photon pair source via spontaneous parametric downconversion in the mid-infrared region

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In recent years, the photon pair generation in the visible (~1 µm) and mid-infrared (MIR) (2-5 µm) wavelength region has been attracting intense attention. They are applied to a lot of applications such as quantum imaging and infrared quantum absorption spectroscopy [1]. With the detection of visible photons, photon pairs can also be used for a heralded MIR single-photon source. However, there have been few detailed evaluations of emitted photons generated in the low gain regime, due to the lack of suitable single-photon detectors.

In this work, we report a wavelength variable visible-infrared photon pair source covering a wavelength range from 2 to 5 µm via spontaneous parametric down conversion (SPDC). By rotating a $LiNbO_3$ crystal, we tune the signal wavelengths from 600 to 965 nm, corresponding to the idler wavelengths in 1186-4694 nm, covering the whole mid infrared region. We also perform coincidence detection of photon pairs up to the wavelength of 2000 nm to confirm the generation of time-correlated photon pairs. Furthermore, we evaluated the flux of the idler photons using an InSb detector with a lock-in detection system up to 5 µm (Fig. 1) [2]. One example of obtained results shows that detected signal in the transmission area of a bandpass filter has the pump polarization dependence as the parametric fluorescence (Fig. 2-a, b). As far as we know, this is the first report of the direct evaluation of SPDC photons in the MIR region over 2.3 µm. From this analysis, a pair generation rate of 10^5 s^{-1} per mW of pump power is experimentally obtained for this wavelength range. These works were supported in part by JST-CREST (JPMJCR1674), Grant-in-Aid from JSPS no. 26220712 and MEXT Q-LEAP (JPMXS0118067634).

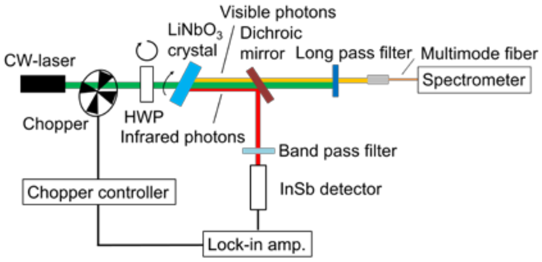

Fig. 1 Experimental setup

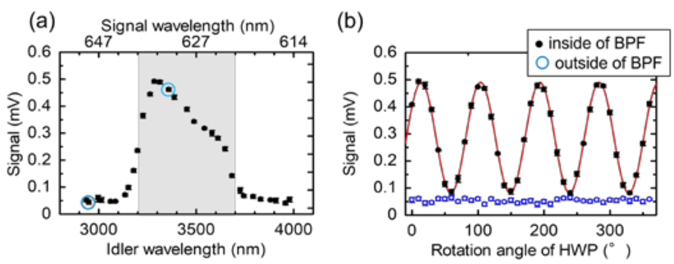

Fig. 2 (a) Wavelength and (b) pump polarization dependence of detected signal of idler photons

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Two-photon excitations with time-energy entangled photon pairs.

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Applications of time-energy entangled photons for stimulating two-photon (2P) processes have been discussed in the literature for a while. A high excitation efficiency using entangled photons for two photon excitation (E2PE) in the linear on the excitation power regime has been a topic of great interest among multiple research groups. Several recent experimental and theoretical studies have raised questions on the practically achievable E2PE enhancement compared to the classical (quadratic) 2P excitation regimes [1,2].
Here we present results of our recent studies of E2PE. Firstly, we discuss the experiments aimed to quantify entangled 2P absorption (E2PA) in several molecules. The results suggest that E2PA cross sections are many orders of magnitude lower than the reported earlier values [1]. We emphasize the importance of conducting additional test of verifying the origin of the signals registered with E2PE and highlight the role of processes like hot band absorption which can mimic E2PA and which should be addressed properly [3]. Secondly, we turn everyone's attention to the process of sum frequency generation with E2PE [4] as a practically useful 'test ground' for studying the transition of linear-to-quadratic E2PE regimes.

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Complex transmittance measurements using quantum Fourier-transform infrared spectroscopy

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Infrared quantum spectroscopy based on quantum nonlinear interferometers enables the determination of infrared optical properties only using visible light sources and detectors [1]. The interference of the visible-infrared photon pair generation processes plays a key role to harness the correlation between the photons with different energies. In a so-called low gain regime, where the average photon flux is below one photon pair per correlation time of the biphotons, the interference process cannot be described by classical theory and should be understood as a result of the quantum interference of the pair generation processes. We developed a theoretical framework to apply Fourier analysis to infrared quantum spectroscopy performed in the low gain regime [2]. The proposed method, quantum Fourier-transform infrared spectroscopy (QFTIR), allows us to extract not only the magnitude of transmittance but also the complex transmittance and optical constants for a sample fully utilizing the phase information of quantum interforgram. As an experimental demonstration, we constructed a Michelson-type quantum nonlinear interferometer (Fig. 1), and measured the complex refractive index for a fused silica glass at around 1550 nm (Fig. 2). The obtained results show a fair agreement with literature values. These results prove the validity and great potential of QFTIR spectroscopy. This work is supported by the MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant No. JPMXS0118067634, JST-CREST (JPMJCR1674), JSTPRESTO (JPMJPR15P4), Grant-in-Aid for JSPS Fellows 20J23408, and WISE Program, MEXT.

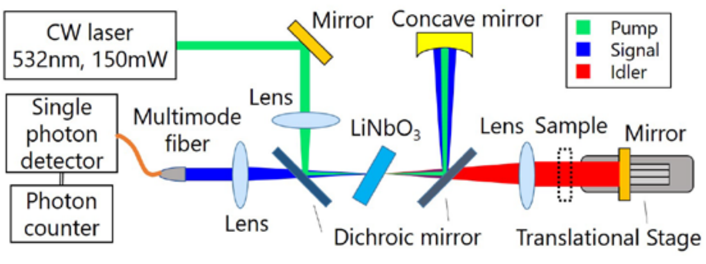

Figure 1. Schematic of experimental setup

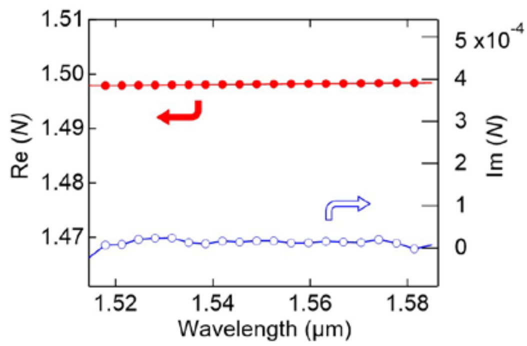

Figure 2. Refractive index for fused silica glass

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Phase sensing using squeezed states of light

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N00N states and other maximally entangled states are highly celebrated for their ability to theoretically provide phase sensing with a sensitivity beyond the standard quantum limit (SQL) and Heisenberg scaling in terms of resources [1]. In practice, these states are probabilistic (for N > 2) and severely impaired by loss and noise. Experimentally breaking the SQL unconditionally using N00N states is very challenging [2].

Squeezed light is a very important continuous variable (CV) state of light, which can provide sensing with sub-SQL sensitivity. Homodyne detection of a pure squeezed state can, furthermore, saturate the Quantum Cramer Rao (QCR) bound [3, 4].

In this work, we present an experimental proof-of-concept demonstration of phase sensing using squeezed states of light, homodyne detection and Bayesian estimation. We achieve sub-SQL sensitivity, out-performing ideal NOON states for low numbers of resources. We also demonstrate an experimental simulation of a sensing measurement of a weak phase encoded signal.

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A Quantum Optical Microphone in the Audio Band

Optical interferometry represents the gold standard for measuring small displacements, refractive index[1], and surface properties[2]. Laser interferometry furthermore enables interaction-free sensing in which precision is ultimately limited by shot-noise. In the past different approaches, surpassing this classical limit using quantum states of light, have been proposed. For example concepts based on heritage schemes are limited by single- or multi-photon detection, which results in low experimental sampling rates[3]. Squeezed-light[4] approaches require complex atom optics setups[5] and/or time-gated detection for post selection, which further hinders applications[6].

We present a novel concept of nonlinear interferometry based on path-polarization quantum state engineering[7]. Here the optical phase of a multi-photon quantum state is inferred in a standard intensity measurement, making single photon detection obsolete. The quantum sensor surpasses the classical shot-noise limit by a factor of 1.13 ± 0.02 for sampling rates between 200 Hz and 100 kHz.

Capitalizing on those advances, we realize a quantum optical microphone in the audio band. Its performance is benchmarked against a classical laser microphone in a standardized medically-approved speech recognition test (Oldenburger Satztest[8]) on 45 subjects. We find that quantum recorded words improve the speech recognition threshold by 0.29 dB with a 95% confidence interval of 0.22 dB, thus making the quantum advantage audible. Not only do these results open the door towards applications in quantum nonlinear interferometry, but also show that humans can directly experience quantum phenomena.

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Controllable discrete-time quantum walk with twisted light

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Discrete-time quantum walks are universal computational primitives [1]. They are used for developing quantum algorithms and state engineering. The universality renders quantum walks as simulators of quantum phenomena such Anderson localization, photosynthesis in plants, extremely slow dynamics in a nonlinear and disordered medium, recurrences phenomena in quantum chaos, quantum field theory for free fermions/fermions, and topological phases of matter [2]. For these applications and unforeseen ones, control over the discrete-time quantum walks is desired and crucial. To this end, we consider a step-dependent protocol for discrete-time quantum walks which enables us readily control the properties of the walks [3]. These walks can be experimentally realized by utilizing a photonic scheme with twisted light in which the photons are walkers and, their orbital angular momentum and polarization are degrees of freedom [4]. By manipulating these degrees of freedom with proper protocols (combination of q-, quarter-, and half-wave plates), we obtain controllable discrete-time quantum walks that can be used for the simulation of topological phases.

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Nonlinear interferometry for broadband infrared sensing

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Infrared (IR) wavelengths is a range of big importance, since many molecules present their fingerprint absorption properties at this region. A promising method for the IR spectroscopy is using an induced coherence phenomenon [1-4], which allows inferring the IR properties of a specimen from the detection of visible light. However, the short optical path of the IR light through the medium under study was one of the limitations of previous IR spectroscopy schemes [3, 4]. Here, we introduce a modified configuration of a degenerate nonlinear interferometer for a broadband IR spectroscopy, where the optical path of the IR light through the medium is increased. We introduce the parabolic mirror into the interferometer, which allows compensating for the transverse phases acquired by SPDC light generated at the forward pass of the pump beam through the nonlinear crystal. Therefore, the interference pattern is observed across the whole spectrum of the SPDC light, see Fig. 1.

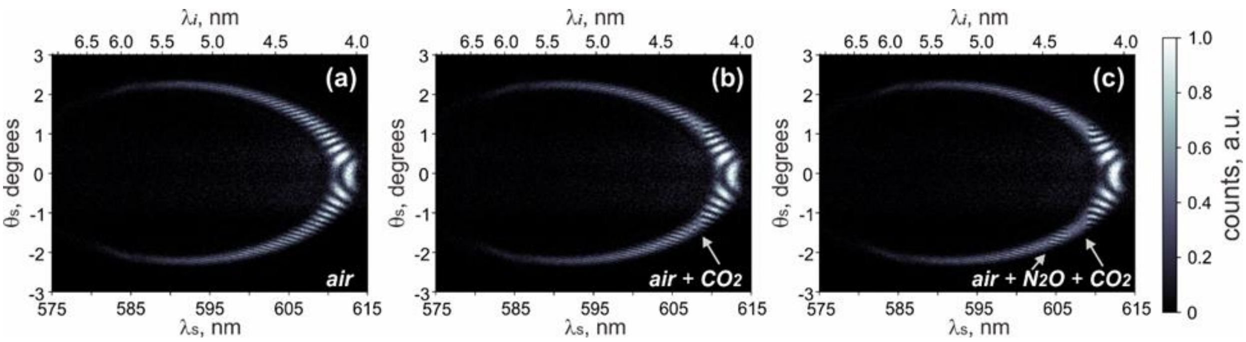

Fig. 1. SPDC spectra generated from $LiNbO_3$ crystal using CW 532 nm laser. Interference patterns for different gas mixtures: (a) an air, (b) an air and CO_2, (c) an air, CO_2 and N_2O. Depending on a gas mixture, the interference fringes disappear at the wavelengths coinciding with the IR absorption lines of gases. Bottom and top x-axis show detected visible photons and conjugate IR wavelengths, respectively.

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Two-colour broadband SU(1,1) – interferometry with dispersion engineered integrated PDC sources

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Interferometry allows us to perform phase measurements with high precision to gain information about a system of interest, e.g., in a classical Mach-Zehnder interferometer. It has been shown that by sending entangled photon pairs into an interferometer, a higher phase sensitivity can be reached [1]. An interesting next idea is to replace the passive beam splitters of a Mach-Zehnder interferometer with active elements, such as parametric down-conversion (PDC) sources. This type of interferometer is called SU(1,1) interferometer [2]. By operating the SU(1,1) interferometer with two non-degenerate wavelengths, for instance in the mid-IR and visible, it becomes possible to retrieve the phase properties of an object interacting with the mid-IR light by measuring the visible light. This is beneficial for applications that pose an upper limit on the amount of light that can interact with a sample, e.g., biophysics, for which a direct detection of the mid-IR light is technically infeasible [3, 4].
Utilising integrated broadband non-degenerate Type-II PDC sources as active elements for such an interferometer enables dispersion sensitive spectroscopy on an object under test due to the broad spectral coverage. Being pumped with a narrow bandwidth CW laser, these PDC sources exhibit strong frequency correlations and simultaneous correlation times between the photons shorter than 100 fs – a signature of entanglement. To benchmark source operation, both spectral and temporal properties must be verified. In general, such short correlation times are hard to measure.
We have shown the fringing pattern of a SU(1,1) interferometer consisting of two such sources as active elements grants access to these correlation times, thus allowing for self-verification of the device. Going beyond this, I will present results on the impact of second order dispersion on the output of the SU(1,1) interferometer and how this could be used for spectroscopy applications. Finally, I will present first measurements of the broadband spectra and their tuneability of the employed group velocity matched PDC sources used as active elements in the interferometer and the effects of such tuning on the correlation time of the photon pair.
To conclude, I will show that a broadband non-degenerate SU(1,1) interferometer provides the possibility to probe the ultra-short correlation time of photons from an engineered PDC source. Furthermore, this interferometer allows for performing dispersion sensitive spectroscopy over a broad frequency range at different colours for probing the sample and detection.

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High-precision multiparameter estimation of mechanical force by quantum optomechanics

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We have addressed a long-standing conceptual inconsistency in the estimation of a weak mechanical force probed by a mechanical oscillator. All current methods approximate small linearized forces by a displacement in position and momentum. However, a linearized force corresponds to a general Gaussian quantum mechanical process affecting the oscillator including both displacement and squeezing of position and momentum. Ignoring these squeezing effects makes the estimation incomplete and imprecise. Moreover, doing so, one can underestimate new mechanical effects and their applications. Taking squeezing into account turns the estimation immediately into a challenging multiparameter estimation problem. We have successfully solved this problem and demonstrated that the weak mechanical force could be indeed entirely characterized while keeping errors small.

On the other hand, the fast estimation of a linearized mechanical force requires the system being in the short-pulsed regime (stroboscopic). In this regime, the limited interaction of mechanical oscillators with light makes the optical readout of the oscillator inefficient. This restriction makes the multiparameter estimation procedure even more complicated. To solve this issue, we propose a scheme that keeps errors small despite the inefficiency of the optical readout and is also robust against the loss and noise involved in the mechanical process. For the first time, such a scheme can detect purely mechanical squeezing induced by the probed mechanical environment. We checked its feasibility for state-of-the-art experimental setups considering as well experiments currently under development.

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

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

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Metasurface-assisted quantum ghost polarimetry

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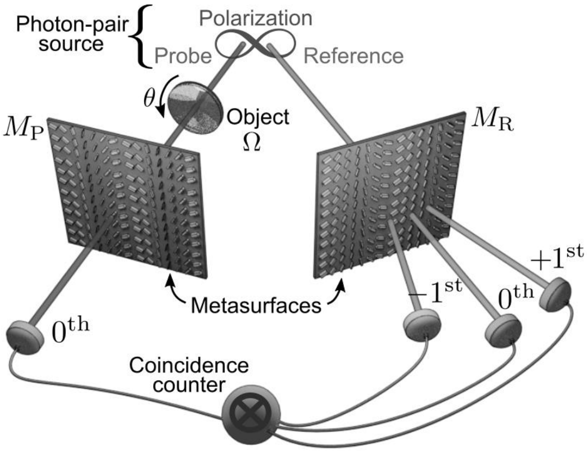
Imaging polarization-sensitive objects is of great importance in fields like biology, where samples are mostly transparent and radiation damage with high-energetic photons should be avoided. However, cameras with high efficiency outside the visible part of the spectrum are costly and have low SNR. Therefore, strong attention has been given to ghost polarimetry as it operates with a source of polarization-correlated photon-pairs that can have nondegenerate wavelengths. In this setup, the sample is illuminated by the photon with longer wavelength and it is measured by a polarization-insensitive bucket detector, while the camera measures only the more energetic “sibling” photon in the visible that never interacts with the object, then the polarization-information of the object is found in the coincidence measurements. Although this concept of ghost polarimetry is not new, there is a fundamental limitation of traditional approaches due to a need for multiple reconfigurable elements which prevents real-time imaging in dynamic environments (see, e.g., Ref. [1]).

In our work, a general model for ghost polarimetry is derived where all-dielectric metasurfaces are used to avoid having reconfigurable elements, see the figure below. These metasurfaces are compact devices that can realize several polarizers in parallel that are in arbitrary elliptical bases with any required extinction ratio [2]. Additionally, our proposed scheme requires only four or less channels in the detection of the non-interacting photon to discriminate fully- or partially transparent objects and their rotation angle. Moreover, we prove rigorously that a source with quantum-entangled photons offers an advantage over classically-correlated pairs.



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Towards QuantumCARS micro-spectroscopy: Interferometric hyperspectral CARS imaging based on broadband correlated photon pairs

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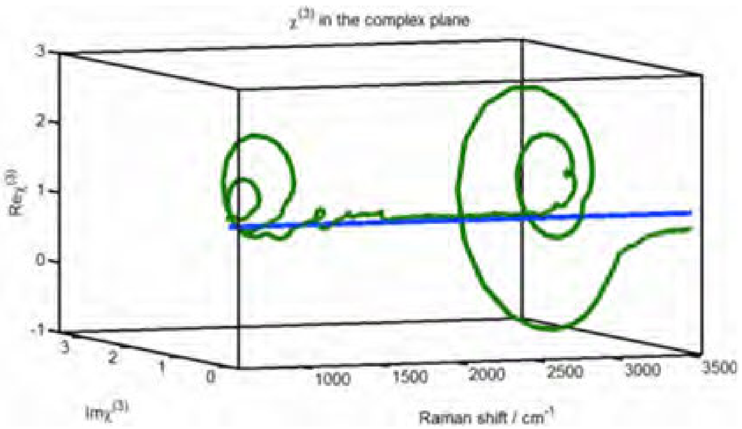
Unlike optical microscopies that are based on fluorescence detection, Raman-based micro-spectroscopies provide vibrational signatures that represent quantitative measures of the sample's molecular composition and structures. In particular, by exploiting the coherent driving and detection of Raman modes in coherent anti-Stokes Raman scattering (CARS) [1,2] and stimulated Raman scattering (SRS) [3], nonlinear Raman scattering imaging offers the highly sensitive point-by-point chemical mapping of molecular compounds, which is often difficult to attain by conventional fluorescence and incoherent vibrational microscopies.

Here, we present the novel concept of QuantumCARS spectroscopy and its proof-of-principle experimental realization of interferometric, hyperspectral CARS imaging based on broadband, correlated photon pairs, which allows direct recording of the amplitude and phase of the complex third-order nonlinear susceptibility $\chi^{(3)}(\nu,x,y,z)$ for each image voxel of an a-priori unknown molecular sample, and demonstrate exemplifying applications for the label-free and noninvasive 3D visualization of its chemical composition and molecular structure.



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Exciton interactions in semiconductor nanocrystals uncovered by spectrally resolved photon counting

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Colloidal semiconductor nanocrystals (NCs) have been among the most widely studied nanoscale light emitters during the last three decades. The absorption of a photon by a NC leads to the formation of an exciton. Absorption of multiple photons leads to the formation of multiple excitons, which interact with each other, which leads to shifts in their energies.

Single NC photoluminescence studies using time-resolved single photon counting (TCSPC) have been instrumental in determining the dynamics of the multiexciton states. However, such approaches typically lack the ability to resolve the energy differences between the excitons at room temperature, where most potential applications of NCs lie.

Our recent work demonstrated that this limitation can be overcome using an array of single photon detectors at the output of a grating spectrometer. Such a setup enables synchronized TCSPC across multiple channels, where each channel corresponds to a different wavelength. The interaction energies of multiple excitons in NCs can be determined by resolving the spectra of photons emitted at each stage of multiexciton recombination, identified by their order of detection [1]. We have recently used this approach to determine the interaction energy of excitons in doubly excited perovskite quantum dots [2]. In larger NCs, it is also possible to study interactions of more than two confined excitons. The poster will contain a description of the state-of-the-art in these measurements.

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Mid-infrared light for non-destructive testing

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Optical coherence tomography (OCT) and infrared (IR) spectroscopy are well known gold standard optical methods for non-destructive testing, research and material characterization. The technical basis for these methods is established and, in most cases, relies on traditional detection solutions and light sources. Recently, the spectacular process of supercontinuum generation (generation of ultra-broadband and ultra-bright spectral continuum), which is, in essence, a cumulative nonlinear phenomenon, has reached not only a significant level of maturity (in terms of noise and stability) but also progressed into the mid-IR spectral range (>2.5 µm wavelength). Due to peculiar emission properties, this evolution has made possible a range of diverse advances in both pure and applied mid-IR photonics – in the spectral range where both detection and generation of light are challenging. Thus, both fields of OCT and IR spectroscopy have been enriched: for OCT deeper penetration depths owing to reduced scattering were demonstrated [1,2], while IR spectroscopy received a bright, spatially coherent, and broadband source of great importance for various scenarios (incl. combination of these methods) [3,4]. We demonstrate the recent achievements in these specific fields.

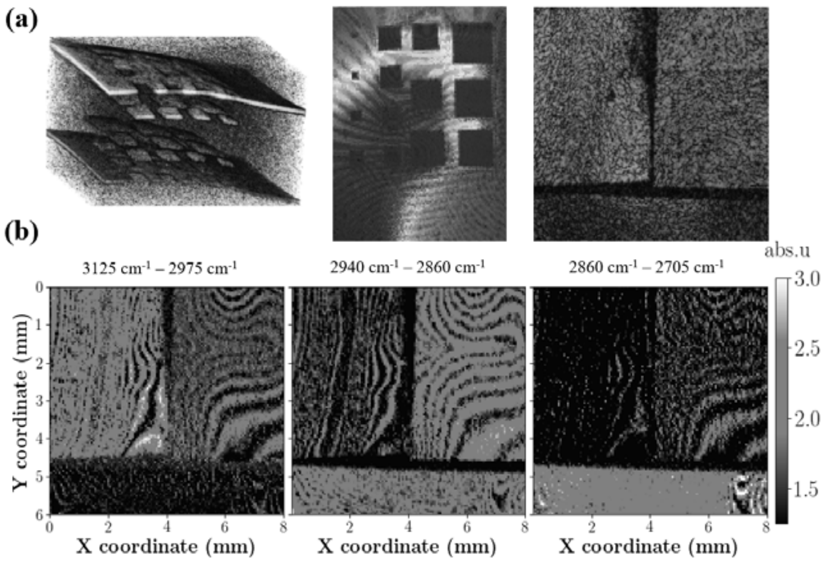

Figure 1: (a) performances of mid-IR OCT structural imaging of scattering ceramics; (b) hyperspectral mid-IR chemical (co-)imaging

References

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