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Abstracts Booklet

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List of abstracts (part 1)

Tailored Non-Gaussian Multimode States

Adrien Dufour, Young-Sik Ra, Thibault Michel, Valentina Parigi, Claude Fabre, Nicolas Treps
Laboratoire Kastler Brossel, Sorbonne Université, ENS-PSL Research University, Collège de France, CNRS;
4 place Jussieu, F-75252 Paris, France
adrien.dufour@lkb.upmc.fr

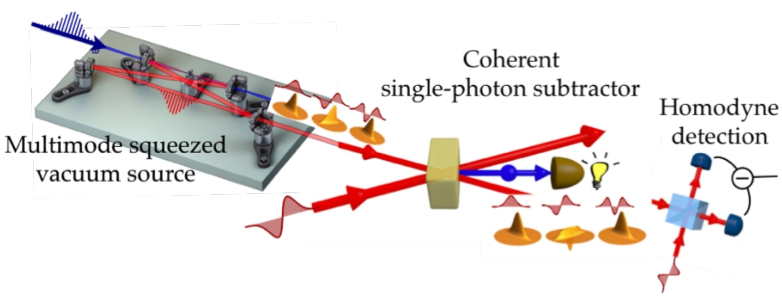
Abstract: We present the generation and characterization of a multimode non-gaussian state. We prepare squeezed vacua in multiple time-frequency modes, subtract a single photon, and then characterize the state by using mode-selective homodyne detection.

In an all-optical setting, there are various approaches to quantum information protocols, often classified according to the way information is encoded and measured. The *discrete variable* approach relates to single photon or photon number resolving detectors, while the *continuous variable* approach (CV) implies homodyne detection to access the quadratures of the electromagnetic field. The major advantage of the latter is the deterministic generation of quantum resources, e.g., entanglement between up to millions of modes [1]. Such multimode entangled states, however, still have Gaussian Wigner functions. Yet, if a quantum information protocol is to manifest a quantum advantage, it requires non-Gaussian operations.

We will present a quantum state that we have been able to generate and measure in our lab, that exhibits both a *high number of modes* and *non-Gaussianity*.

It has been implemented by incorporating single-photon subtraction to a purely CV scheme [2]. Using a source of multimode squeezed states based on parametric down conversion of an optical frequency comb [3], we performed photon subtraction on a coherent superposition of time/frequency modes [4]. This was achieved using a sum-frequency process between the quantum source and an intense gate beam. Full control on the gate beam time/frequency modes governs the modal decomposition of the process. State tomography is performed via homodyne detection, where the local oscillator beam is pulse-shaped in order to achieve mode-dependent quadrature measurement.

Negative Wigner function states can be obtained, choosing which of the eigenmodes of the quantum source is affected by the de-Gaussification. Furthermore, in this multimode scenario, mode dependent detection allow for the generation of graph-states [5]. We study the effect of coherent photon subtraction onto these graph states [6, 7] and demonstrate experimentally that the non-gaussian character induced by photon-subtraction spreads along the graph state, but that the spread is fundamentally limited by the nature of these states. This can serve as a guide to tailor large-scale non-Gaussian states for quantum information processing.



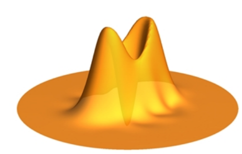


Fig.1 (left) : experimental scheme
Fig.2 (up) : Wigner fonction in the first mode, after subtraction in this mode. It has some negative part around the origin, where W(0,0) = -0,108/2π

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Two-Photon Joint Spectral Wave Function Measurement

Alex O.C. Davis[1], Valérian Thiel[1], Brian J. Smith[1,2]

[1]*Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH*
[2]*Department of Physics and Oregon Center for Optical, Molecular, and Quantum Science, University of Oregon, Eugene, OR 97403, USA*
alex.davis@physics.ox.ac.uk

Abstract: We present a technique to completely characterize the joint spectral-temporal wave function of a broadband photon pair at 830 nm center wavelength using spectral-shearing interferometry. Our fully self-referencing method applies spectral shear using electro-optic modulation.

The ability to characterize quantum states of light is an essential prerequisite for all optical quantum technologies including quantum computing [1,2], quantum key distribution [3], and quantum-enhanced sensing [4]. Development of sources and detectors of quantum optical states requires accurate reconstruction of the field modes with which they interact, and dependable state reconstruction is an important tool for standard quantum process tomography [5]. For quantum states it is important to have a characterization scheme that is sensitive to the nonclassical correlations that can exist between separate subsystems. Quantum correlations between photon pairs can arise in any of the physical degrees of freedom of light, such as polarization [6], transverse spatial mode [7] and the longitudinal, or time-frequency (TF), state [8]. Recently quantum states of light occupying spectrally broadband pulsed TF modes have attracted interest due to their potentially large information content and compatibility with integrated optical platforms. Technologies to produce such states, e.g. spontaneous parametric downconversion (SPDC) sources, are well-developed and can produce photon pairs in orthogonal modes with high-dimensional entanglement in the TF basis. The two-photon TF wavefunction $|\psi\rangle$ can be completely expressed in terms of the complex-valued joint spectral amplitude function $f(\omega_1,\omega_2)$ [9] such that

$$|\psi\rangle = \int f(\omega_1,\omega_2) a^\dagger_{\omega_1} b^\dagger_{\omega_2} d\omega_1 d\omega_2 |\mathrm{vac}\rangle \tag{1}$$

where $a^\dagger_{\omega_1}$ and $b^\dagger_{\omega_2}$ are operators that act on the vacuum to create a single monochromatic photon in their respective modes with frequency ω_1 and ω_2. All spectral-temporal properties of the photon pair, including TF entanglement, are determined by $f(\omega_1,\omega_2)$. However, techniques to completely characterize this two-photon joint state have yet to be developed. Previous work on photon pairs has mainly focused on partial characterization of the two-photon state through measurement of the joint spectral intensity [10] or joint temporal intensity [11]. However, these approaches suffer from the major drawback that they are phase-insensitive and are not sufficient for complete state reconstruction. Sources based on parametric fluorescence processes such as SPDC or four-wave mixing can be characterized by studying the corresponding stimulated processes such as difference frequency generation, but this requires a tunable, spatially mode-matched and well-characterized second pump field as well as classical characterization techniques, and is not applicable for other types of source [12,13]. Full characterization of the TF wave function of heralded single photons without the need for a reference signal or *a priori* knowledge of the mode has been recently demonstrated by electro-optic spectral shearing interferometer (EOSI) [14]. An EOSI works by sending a single pulse with complex spectral amplitude $\phi(\omega)$ into an unbalanced Mach-Zehnder interferometer with a relative optical delay of τ and an electro-optic modulator in one path applying a constant angular frequency shift Ω. Spectrally-resolved measurement at the outputs reveal an interference pattern

$$I(\omega,\Omega,\tau) = \frac{1}{2}\left[|\phi(\omega)|^2 + |\phi(\omega+\Omega)|^2\right] + Re\{\phi^*(\omega+\Omega)\phi(\omega)e^{i\omega\tau}\}, \tag{2}$$

from which the spectral phase can be determined [15,16]. Here we extend this idea to the two-photon case and present a method for complete photon pair TF state characterization. Detection of the first photon in a narrow spectral bin centered on ω_M projects the second photon into a state $\int f(\omega_M,\omega_2) b^\dagger_{\omega_2} d\omega_2 |\mathrm{vac}\rangle$, which is reconstructed by the EOSI. This measurement is repeated for multiple values of ω_M until the entire spectrum of the first photon has been sampled. This procedure is then repeated in the other configuration, with the second photon undergoing spectrally-resolved detection and the first sent into the EOSI, in order to establish both the amplitude and phase of $f(\omega_1,\omega_2)$ as a function of both frequencies.

Spectrally decorrelated broadband photon pairs were generated with central wavelength of 830 nm by an 8 mm-long potassium di-hydrogen phosphate (KDP) crystal SPDC source pumped at 80 MHz with pulses at 415 nm central wavelength, derived from ultrashort frequency-doubled pulses from a Ti:Sapphire laser oscillator (SpectraPhysics)[17]. The procedure for using EOSI for full two-photon TF state characterisation is as follows. Spectral phase correlations in the photon pair are generated by applying large group delay dispersion to the 415 nm pump by placing a 100 mm block of dispersive BK7 glass in the beam path. This creates a correlated term in the spectral phase profile of the form $\phi_{\mathrm{corr}} = \phi_{12}\omega_1\omega_2$. The heralding photon undergoes direct spectrally-resolved detection in a time-of-flight spectrometer [18]. The signal photon is then sent into the EOSI with the outputs measured in coincidence with the herald. This creates spectral interference patterns which vary depending on the spectral position of the heralding filter, indicating non-separability of the joint spectral amplitude $f(\omega_1, \omega_2)$. This procedure is then repeated in the configuration where the role of the photons is swapped. In summary we have shown the ability to characterize broadband photon pairs exhibiting non-local phase correlations. These results have significant implications for quantum state tomography and high-dimensional entangled source characterisation.

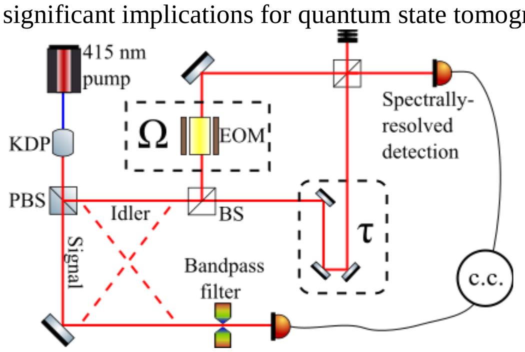

Figure 1: Schematic of experimental set-up. One photon of a pair is split and has frequency shift Ω and relative time delay τ introduced before spectrally-resolved detection at a beam splitter. The other is spectrally filtered and measured in coincidence. The photons are then swapped for full reconstruction.

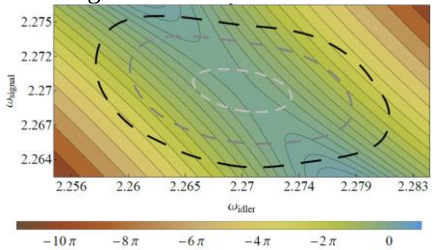

Figure 2: Full phase-sensitive reconstruction of a two-photon joint spectral-temporal wave function. Background colour indicates the phase of the complex joint spectral amplitude $f(\omega_1, \omega_2)$ whilst the grayscale contours show lines of constant amplitude $f(\omega_1, \omega_2)$

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INTERFERING PHOTONS IN ORTHOGONAL STATES

Alex E Jones[1,2], Adrian J Menssen[1], Helen M Chrzanowski[1], Valery S Shchesnovich[3], Ian A Walmsley[1]
[1] *Department of Physics, University of Oxford, United Kingdom*
[2] *Department of Physics, Imperial College London, United Kingdom*
[3] *Center for Natural and Human Sciences, Federal University of ABC, Brazil*

e-mail: a.jones14@imperial.ac.uk

Quantum interference gives rise to behaviour that cannot be described classically. The famous experiment by Hong, Ou and Mandel demonstrated the connection between the strength of the interference of two independent particles and the pairwise distinguishability of their quantum states: bunching at the outputs of a balanced beam splitter increases as the states become more similar [1]. Over the last 30 years this effect has been exploited in developing quantum technologies yet, despite this ubiquity, there are still surprises: here we show that independent photons prepared in orthogonal states can still exhibit quantum interference.

On extending the study of multiphoton interference to more than two photons, pairwise distinguishabilities are no longer sufficient to fully describe the statistics in an interference experiment [2]. Crucially there is now sensitivity to the phases of the inner products of the participating quantum states. As long as none of the participating photons are in orthogonal states, it is possible to decompose higher order phases into three-particle phases [3]. However if this condition is broken, collective phases can persist that are no longer decomposable into lower-order phases. For the case of four photons, it is possible to prepare pairs of states to be orthogonal, but maintain a collective four-photon phase that influences coincidence statistics in an interference experiment. In other words, photons in orthogonal states can still show quantum interference!

To demonstrate this experimentally, we use two parametric down-conversion (PDC) sources to prepare four photons, two of which are orthogonal in polarisation and the other two distinguishable in time (Fig. 1a). These are injected into a 4x4 balanced splitter and coincidence statistics are collected at the outputs (Fig. 1b).

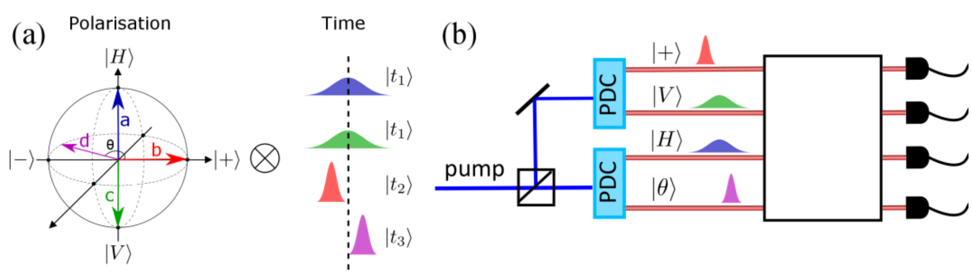

Fig. 1 (a) State preparation such that state a(b) is orthogonal to state c(d). (b) Experimental setup.

The collective four-particle phase is varied by rotating particle *d*'s polarisation in the equatorial plane of the Poincaré sphere. This ensures no three-particle interference, and the pairwise distinguishabilities of the states remain constant so two-particle interference is unchanged. The four-fold coincidences vary as a function of this phase, whilst all lower-order correlations remain constant. We identify this as interference of photons in orthogonal states that cannot be attributed to variations of lower-order correlations.

Keywords: quantum interference; distinguishability; photons

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Direct characterization of temporal phase modulation patterns applied to optical pulses

Ali Golestani, Michał Jachura, Filip Sośnicki, Michał Karpiński
Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warszawa, Poland

Temporal-spectral modes of light are considered as robust candidate for performing various information encoding. This degree of freedom can be employed in quantum regime in order to realize high dimensional quantum networks. This feature requires the development of a variety of techniques for spectral and temporal manipulations of single photons. Here we present characterization of temporal electro optic phase modulation (EOPM) applied to optical pulses which has capability to be utilized in quantum regime.

In order to implement temporal phase modulation, we use electro-optics phase modulator for controlling phase of the optical pulse via an electrical signal. This allows us to preserve fragile nature of the quantum state of light [1]. Note that coherent manipulation of the optical pulse is performed by applying the phase modulation in a regime where the optical pulse duration is shorter than variations in the phase modulation signal. We need to probe temporal phase modulation patterns because it gives capability to shape spectra of the both quantum and classical light pulses. We discuss two alternative approaches to directly characterize the temporal phase modulation patterns applied to optical pulses based on spectral and temporal interference.

In the spectral interference approach, a chirped pulse is sent into two arms of an unbalanced Mach-Zehnder interferometer (MZI) [2]. In one of its arms temporal phase modulation is applied so that the chirped pulse, with different wavelengths spreading in time, experiences different spectral shifts. By implementing this time to spectral mapping, the temporal phase modulation is encoded in the spectral phase which we read out by spectral interferometry. This gives us encoded temporal phase just in a single spectrum but the issue is that it is difficult to realize single shot or pulse by pulse measurements at high repetition rates.

In contrast, the temporal interference approach enables easy acquisition of temporal phase modulation values on a pulse by pulse basis, which is necessary for timing jitter characterization. In the temporal interference approach, un-chirped pulses are sent into a balanced MZI, where temporal phase modulation is applied in one of the arms. At the interferometer output intensity measurements with a single photodiode enable monitoring of temporal phase modulation at a given point in time. To obtain the temporal phase modulation profile we scan the delay of the probe pulse with respect to the temporal phase modulation pattern. Although the technique requires scanning to obtain a complete phase modulation profile, it allows probing the timing jitter at repetition rates limited only by the photodiode bandwidth.

In summary, we developed optical setups for characterization of temporal phase modulation by spectral and temporal interference. We evaluate their performance for directly measuring temporal phase modulation profiles and performing timing jitter measurements. The techniques form a robust platform for characterization of electro-optic phase modulation devices for spectral-temporal pulse shaping in both classical and quantum regime.

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Observation of Photon-Subtracted Two-Mode Squeezed Vacuum States

A. Perez-Leija[1,2], O. S. Magaña-Loaiza[3], R. de J. León-Montiel[4], K. Busch[1,2], A. E. Lita[3], S. W. Nam[3], T. Gerrits[3] and R. P. Mirin[3]

[1] *Max-Born-Institut, Max-Born-Straße 2A, 12489 Berlin, Germany*
[2] *Humboldt-Universität zu Berlin, Institut für Physik, Newtonstraße 15, 12489 Berlin, Germany*
[3] *National Institute of Standards and Technology, 325 Broadway, Boulder Colorado 80305, USA*
[4] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, A. P. 70-543, 04510 Cd. Mx., México*

Abstract: We experimentally demonstrate that simultaneous subtraction of photons from two-mode squeezed vacuum states leads to the generation of entangled states with a larger average photon number. This technique allows for the engineering of a novel family of entangled multiphoton states with tunable mean photon numbers and degrees of entanglement.

The creation of highly nonclassical states is one of the most challenging tasks in quantum optics. In particular, multiphoton entangled states and coherent superpositions are very useful as resources for optical quantum information processes and metrology [1]. Currently, the most accessible multiphoton sources are two-mode squeezed vacuum states (TMSVS), which are based on the process of spontaneous parametric down-conversion (SPDC) from a nonlinear crystal [1]. In this contribution, we demonstrate the generation of photon-subtracted entangled states utilizing a bright source of spontaneous parametric down-conversion in combination with photon-number-resolving detectors [2].

For our experiments, we have used a Ti:Sapphire laser and a spectral shaper, composed by two gratings an a $4f$ optical system, to produce 1 ps optical pulses that are used to pump an $L = 8$ μm long periodically poled KTP (ppKTP) waveguide. This configuration allows us to produce bright TMSVS at 1570 nm by means of an SPDC type-II. Ideally, the states produced by our source can be described by $|z\rangle = \sqrt{1-|z|^2}\sum_{n=0}^{\infty} z^n |n\rangle_s |n\rangle_i$, where n is the number of photons in the signal (s) and idler (i) modes, and $z = \tanh(r)$, with $r = \chi_{\text{eff}}\omega_p L\sqrt{I_p}/(2n_0c)$ being the squeezing parameter, defined in terms of the refractive index n_0 and the effective nonlinearity χ_{eff} of the waveguide, and the frequency ω_p and intensity I_p of the pump field.

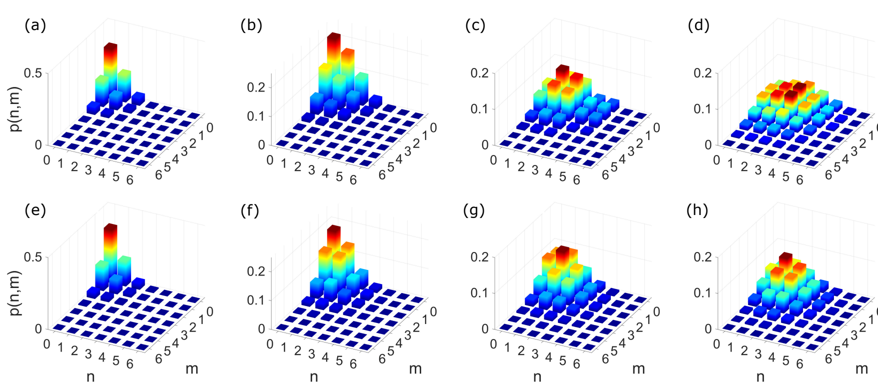

Fig. 1. (Top row) Experimental joint photon distributions (top row) for different number of subtracted photons: (a,e) $l = 0$, (b,f) $l = 1$, (c,g) $l = 2$, and (d,h) $l = 3$. (Bottom row) Theoretical predictions obtained by evaluating the photon number distributions of the photon subtracted states with an squeezing parameter $z = 0.67$.

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Machine learning for enhanced atom-light interactions

Ben Buchler, Jesse Everett, Young-Wook Cho, Aaron Tranter, Harry Slatyer, Michael Hush, Karun Paul, Pierre Vernaz-Gris, Anthony Leung, Daniel Higginbottom, Ping Koy Lam and Geoff Campbell

Centre for Quantum Computing and Communication Technology (CQC2T)
Research School of Physics and Engineering, Australian National University, Canberra ACT 2601, Australia
Author e-mail address: ben.buchler@anu.edu.au

In our experiments we use a laser-cooled ensemble of rubidium 87 atoms to manipulate the propagation of light. The motivation for this work is the control of quantum information in a quantum processing network [1,2]. In particular we investigate the use of *stopped* and *stationary* light.

Stopped light is an optical field that has been fully mapped into a coherence (spinwave) of the atomic ensemble. In this case the optical field amplitude falls to zero. Low-loss, reversible mapping of light into and out of a stopped state can be used for optical quantum memory [3]. In our Gradient Echo Memory (GEM) we have demonstrated storage of light with a maximum short-time efficiency of 87% [4]. The decay time for our cold-atom memory can be as long as 1ms.

Stationary light is an optical field that is bright, yet has a group velocity of zero and is unable to propagate [5]. Proving that stationary light exists requires indirect measurement since the stationary light, by definition, cannot be measured in-situ. In our experiments we image the atomic spinwave at different time steps in a stationary light experiment allowing direct comparison [6] with modelling (Fig. 1a). Stationary light, because it is bright, could be used to enhance weak optical nonlinearities such as cross-phase modulation, allowing the construction of deterministic nonlinear quantum gates [7].

All our experiments take place in a laser-cooled ensemble of atoms that is formed using a magneto-optic trap (MOT). Maximising the optical coupling to this ensemble requires trapping and cooling the highest possible number of atoms. Even with decades of research and engineering, however, there is no proven recipe to maximise atom number and minimise temperature. This is because, without valid simplifying assumptions [8], these systems work in a computationally intractable regime involving many body interactions and complex scattering dynamics. Improving the optical depth of a MOT has mostly been limited to intuition based on adiabatic approximations and trial-and-error.

In our experiment we have recently begun using machine learning to accelerate the trial and error approach [9]. Our system uses the M-LOOP package [10] with an artificial neural network. The machine is tasked with maximising the on-axis optical depth of the atomic cloud. We give the learning algorithm control of three physical parameters: trapping field detuning, repump field detuning and trapping coil current (Fig. 1b). Measured along the axis of the atom cloud (using the $|1\rangle \rightarrow |2\rangle$ transition of the rubidium D1 line) the best human optimised optical depth in our system was 530 ± 8 whereas the machine achieved 970 ± 20. This improvement was stable over many months. We anticipate that this larger optical depth will lead to enhanced performance of all our quantum atom-light experiments in the future.

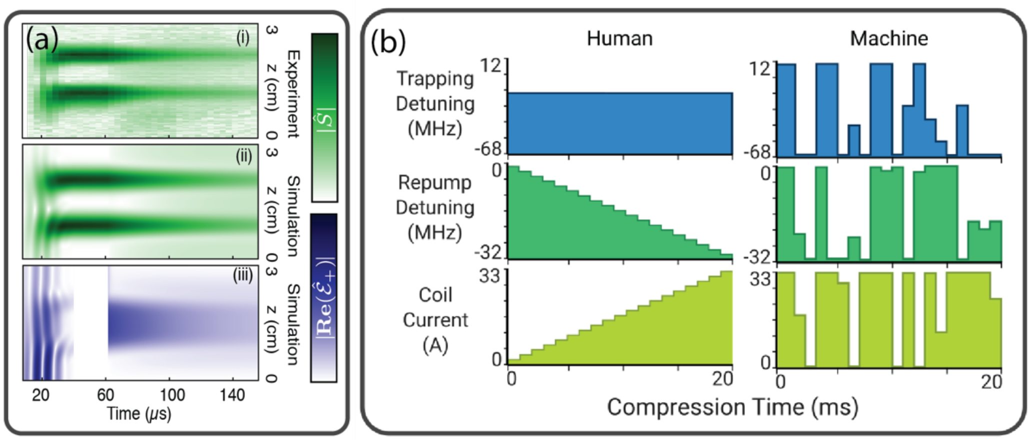

Figure 1: (a) Stationary light data. (i) Experimental measurements of the spinwave performed with absorption imaging; (ii) numerical model of the spinwave based on experimental parameters; (iii) corresponding stationary light amplitude. (b) A comparison of the best human and machine optimized MOT parameters. The machine learner had control over 3 physical variables each with 21 time-steps, giving a total of 63 free parameters.

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Nonclassicality quasiprobabilities certify quantum non-Gaussianity and quantify nonclassicality

Benjamin Kühn and Werner Vogel

Arbeitsgruppe Theoretische Quantenoptik, Institut für Physik, Universität Rostock, D-18051 Rostock, Germany

benjamin.kuehn2@uni-rostock.de

Abstract:
Nonclassicality quasiprobabilities are regular, experimentally accessible phase-space functions, which uncover all nonclassical properties of light [1]. The nonclassicality is defined on the basis of negativities of the Glauber-Sudarshan P function [2–4]. In practice it is important to give more specific structural information on the state, beyond the bivalent categorization in classical and nonclassical states. Especially the strength of nonclassicality is relevant to compare different quantum light sources with respect to their utility in quantum technological applications. One possibility for such a nonclassicality measure is the algebraic approach of counting the number of quantum superpositions of coherent states [5]. Furthermore, for the experimental generation of a desired quantum state one also may investigate whether this state can be conveniently produced in experiment by applying adequate classical noise to a light source, emitting Gaussian states. On the other hand if the state cannot be produced by classical processes on Gaussian states, the state is called quantum non-Gaussian [6] and its experimental preparation relies on fundamentally different quantum light sources.
We show that both quantum non-Gaussianity and the degree of nonclassicality are directly apparent in the nonclassicality quasiprobabilities [7]. Interestingly, when the nonclassicality quasiprobabilities approach the P function, which is achieved by increasing a free filter parameter, the resolvable nonclassicality degree can be arbitrarily increased.
In addition, we propose a classical process to prepare light in a nonclassical state with regular P function [8], provided that it is fed with an arbitrary nonclassical input. This is realized by a linear optical device, essentially composed of a single highly transmissive beam splitter and an engineered classical field. In this way the regularization of the P function of quantum states is performed before any measurement, such that the resultant state is available as a resource for further quantum applications.

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Multi-photon interference in the frequency domain via direct heralding of superposition states

Bryn A. Bell (*Clarendon Laboratory, University of Oxford, UK*) and Benjamin J. Eggleton (*School of Physics, University of Sydney, Australia*).

Optical quantum information processing and quantum simulation rely on the interference of many single photons in many-mode interferometers. It appears challenging to reach the scale where experiments exceed the performance of classical super-computers (requiring around 50 photons in ~1000 interfering modes), due to the difficulty in preparing that many single photons simultaneously, controllably interfering that many modes, and avoiding photon loss throughout. Recently there have been several proposals to build interferometers that take advantage of the large number of frequency modes or temporal modes available within a single optical fibre [1,2].

Here, we demonstrate multi-photon interference using frequency modes without applying a unitary transformation after the quantum light source. Instead, the frequency correlations, or joint spectral amplitude (JSA), of the source are configured such that photons are directly heralded in superposition states across several modes. Then, interference is seen when the photons are measured in the frequency basis, without the need for further manipulation.

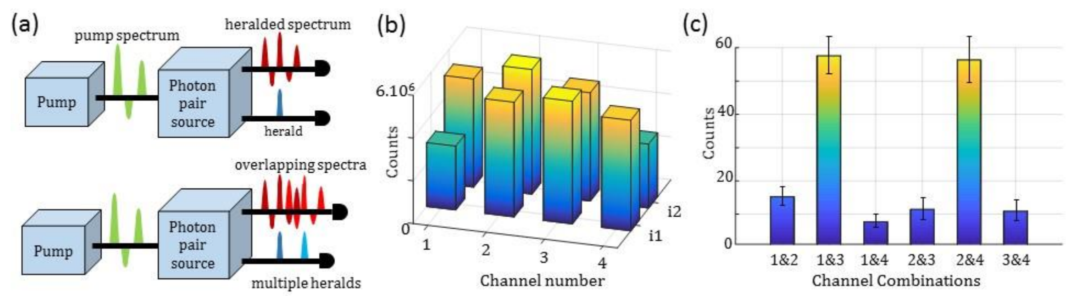

Fig. 1. (a) Photon generation with a shaped pump spectrum, leading to heralded photons in frequency superpositions. (b) Two photon events between signal channels 1-4 and idler channels i1,i2. (c) four photon events when an idler is detected in i1 and i2.

First, spectral pulse-shaping is used to prepare a laser pulse with arbitrary spectral intensity and phase profile. This pumps a photon pair source based on four-wave mixing in a silicon waveguide, which can create signal/idler pairs over a large bandwidth. An idler photon generated at a particular frequency heralds a signal photon with a spectrum determined by that of the pump pulse [3], which can extend across multiple frequency channels (Fig. 1(a)). When two idlers are detected simultaneously at two different frequencies, the spectra of the corresponding signals can overlap, giving rise to multi-photon interference. Fig.1(b) and Fig.1(c) show the measured two photon and four photon event rates respectively, where the phase profile of the pump has been chosen such that an interference pattern can be seen in the four photon events which is not apparent from the two photon events alone.

This scheme benefits from a compact experimental setup where the complexity is shifted to preparing the classical pump, rather than the single photons. It could be applied to scaling up Gaussian boson sampling experiments to more modes and higher photon numbers, since it is essentially generating a multi-mode squeezed vacuum state and then making photon-counting measurements.

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Certification of Gaussian Boson Sampling Using Two-Point Correlation Functions

Expanding on the previous work by Walschaers *et al* [1], we will explore the statistical signatures obtained from Gaussian Boson sampling (GBS). We will show that it is possible to derive a general expression for the two-point correlation function for two arbitrary output modes when squeezed vacuum states are evolved under Haar-random unitaries, without having to project onto the photon-number basis. We will explain that it is possible to certify Gaussian Boson sampling using quantum squeezed vacuum states against classical thermal and coherent states by comparing the obtained statistical signatures of the two-point correlations from many different Haar-random unitaries. We will discuss the limits on error tolerance of the distribution moments by comparing the results from various sample sizes with the analytical results from random matrix theory. Finally we will investigate the effects of experimental limitations of GBS certification by exploring system loss and finite sample sizes.

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Bloch-Messiah reduction for twin beams of light

D. B. Horoshko[1, 2] and M. I. Kolobov[1]

[1] *Univ. Lille, CNRS, UMR 8523 - PhLAM, F-59000 Lille, France*

[2] *B. I. Stepanov Institute of Physics, NASB, Minsk 220072 Belarus*

Bloch-Messiah reduction [1, 2] is a key procedure for description of multimode states of light generated via nonlinear interactions with second-order Hamiltonians, like parametric downconversion (PDC). It allows one to represent the generated field as a collection of statistically independent "squeezing eigenmodes", each being in a single-mode squeezed state characterized by some mode-dependent degree of squeezing. The study of distribution of squeezing between different modes and of the possibilities to affect it by phasematching and pump shape engeneering represent an interesting and highly practical problem, important for development of sources of quantum states for quantum communication and quantum information processing with continuous variables of light.

In the present work we consider generation of twin beams of light via PDC [3]. We write the annihilation and creation operators of $n = 2m$ optical modes as a column vector $\mathbf{a} = (a_1, ...a_n, a_1^\dagger, ..., a_n^\dagger)^T$. A Gaussian unitary transformation in PDC with undepleted pump is characterized by an evolution operator $\mathcal{U} = \exp(-i\mathcal{H})$, where the Hermitian operator $\mathcal{H} = \frac{1}{2}\mathbf{a}^\dagger\mathbf{H}\mathbf{a}$ is called transformation generator and is a second-order polynomial of $\mathbf{a}$. The case of twin beams corresponds to the following structure of the transformation generator matrix:

$$\mathbf{H} = \begin{pmatrix} 0 & 0 & 0 & J \\ 0 & 0 & J^T & 0 \\ 0 & J^* & 0 & 0 \\ J^\dagger & 0 & 0 & 0 \end{pmatrix}, \tag{1}$$

where J is a complex $m \times m$ matrix, known as joint spectral amplitude for two photons generated in an elementary nonlinear process. In the case of twin beams these two photons are generated into two distinct modes, differing by direction, wavelength or polarization, which corresponds to non-collinear, non-degenerate or type-II phasematching.

We study the distribution of squeezing between the eigenmodes of twin beams and find a fundamental result: double degeneracy of degree of squeezing. In other words, the eigenmodes create pairs with the same degree of squeezing. As consequence, the twin beams eigenmodes are not unique and defined up to orthogonal rotation in the degenerate subspace. We show that the eigenmodes are delocalized in the sense that their modal functions include both directions (wavelengths, polarizations) and the orthogonal rotations leave this property unchanged.

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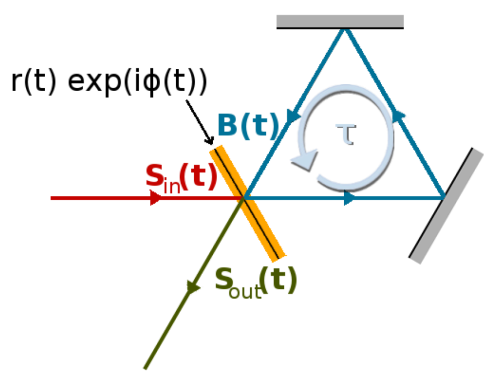
A temporal-mode selective device using linear optics – the electro-optic cavity

Leon Berrisford [1], Dileep Reddy[4], Amir Feizpour[1], Sarah Thomas[1,2], Joseph Munns[1,2], Patrick Ledingham[1], Benjamin Brecht[1], Josh Nunn[3], Michael Raymer[4], Ian Walmsley[1] and **Dylan Saunders[1]**

[1]Clarendon Laboratory, University of Oxford, UK
[2]Blackett Laboratory, Imperial College London, UK
[3]Centre for Photonics and Photonic Materials, University of Bath, UK
[4]Department of Physics and Oregon Center for Optical, Molecular, & Quantum Science, University of Oregon, Eugene, Oregon 97403, USA

We present a theoretical analysis of a new method of light mode selection via an adjustable coupling to a cavity. The cavity is constructed around a Mach-Zehnder interferometer, with electro-optic modulators being used to vary the effective reflectivity properties of the cavity, and consequently both the selected and output modes. The analysis here derives the required reflectivity profile of the cavity to achieve both input and output mode selectivity. A computational analysis is then performed to explore the validity of various assumptions. This showed that in the bad cavity limit with a pulse length greater than around 10 cavity round-trip times τ that mode selectivity can be achieved with an error of ~ 0.5% in the lossless case. The error decreases to zero with increasing pulse length. It is also found that known constant round trip losses can be accounted for, resulting in similar orders of error as in the lossless case if the reflectivity profile is adjusted accordingly.

This device in principle is compatible with integrated optics – allowing for temporal mode selective devices to produced on chip – which may find use in spectral purification of PDC devices on chip. The bandwidth of the device is limited by the speed of integrated modulators, and thus compatible of GHz operation bandwidths.



Schematic of the Electro-Optic-Cavity – by varying the complex reflectivity of the cavity, the device can filter out a single temporal mode.

Time-dependent nonlinear Jaynes-Cummings dynamics of a trapped ion

F. Krumm and W. Vogel

Arbeitsgruppe Theoretische Quantenoptik, Institut für Physik, Universität Rostock, D-18051 Rostock, Germany

The verification and quantification of nonclassical effects, that is, phenomena which cannot be explained by Maxwells equations, is a main concern of theoretical and experimental quantum optics. Many of those effects, like squeezing, entanglement, and photon antibunching, were intensively investigated over many decades. However, there are effects beyond this set, like, for example, anomalous quantum correlations [1], which arise from the violation of field-intensity inequalities. In such and related scenarios a subject of interest is the investigation of the interplay of free fields and fields which are attributed to sources.

Hence, the treatment of a physical system containing contributions from both kinds of fields is an interesting aspect to be studied, especially when the corresponding dynamics is exactly solvable. A suitable model for this purpose is for example the nonlinear Jaynes-Cummings model, describing the quantized center-of-mass motion of a trapped ion [2], which contains not only free-field parts but a source-attributed part as well. To further increase its versatility we consider the system not being in perfect resonance with the classical driving laser.

The scheme of the detuned nonlinear Jaynes-Cummings model's dynamics is depicted in Fig. 1: The two electronic states, ground state $|1\rangle$ (lower potential-energy surface) and excited state $|2\rangle$ (upper potential-energy surface) are separated by the electric transition frequency $\omega_{21} = \omega_2 - \omega_1$. Since the (harmonic) trap potential is not influenced by the ion dynamics, the energy surfaces are neither displaced, nor distorted and the vibronic levels are separated equidistantly by ν. The laser frequency $\omega_L = \omega_{21} - k\nu + \Delta\omega$ (red arrows) is not in exact resonance with the $|1, n\rangle \leftrightarrow |2, n-k\rangle$ transition, but slightly detuned by $\Delta\omega$.

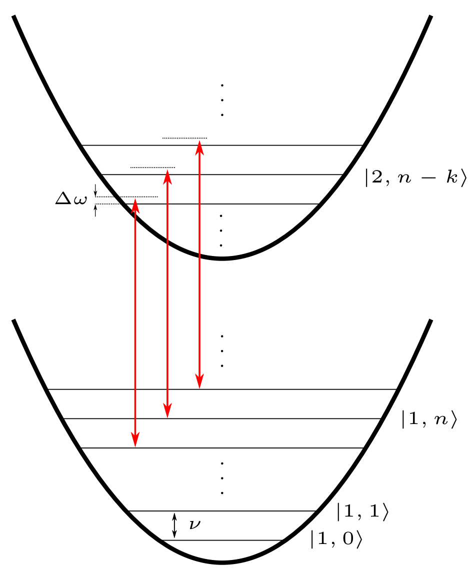


Figure 1

The admittance of a detuning, however, yields an explicit time dependence in the corresponding Hamiltonian. Thus, time-ordering effects need to be taken into account and finding an (exact) solution might be a cumbersome task. We show that describing the pump field in a quantized manner, that is extending the Hilbert space, leads again to a time-independent Hamiltonian which can be solved exactly [3]. Using the derived solution, we verify that for a strong coherent driving field the (numerically) calculated semiclassical solution is recovered, which is now only a special case in our model.

Furthermore, we present an algorithm to calculate the regularized Glauber-Sudarshan phase-space representation [4, 5] out of the (reduced) density matrices in Fock basis. The occurring negativities of this quasiprobability are a clear certifier of the nonclassical character of the trapped ion's vibrational states for different points in time. In conclusion, we derived exact solutions of the detuned nonlinear Jaynes-Cummings model without additional approximations and, hence, we believe that this versatile model may serve as physical playground for many aspects of time ordering in quantum optics.

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Quantum Correlations in Nonlocal BosonSampling

Farid Shahandeh[1], Austin P. Lund[1], and Timothy C. Ralph[1]

[1]*Centre for Quantum Computation and Communication Technology, School of Mathematics and Physics, University of Queensland, Brisbane, QLD 4072, Australia*

Determining whether the correlations between two systems are quantum or classical is fundamental to our understanding of the physical world and our ability to use such correlations for technological applications. In quantum information theory, quantification of quantum correlations is mainly based on the notion of quantum entropy [1].

In contrast, in quantum optics it is common to study nonclassical features of bosonic systems in a quantum analogue of the classical phase space. While in a classical statistical theory in phase-space the state of the system is represented by a probability distribution, the quantum phase-space distributions can have negative regions, and hence, fail to be legitimate probability distributions [2]. The negativities are thus considered as nonclassicality signatures. Within multipartite quantum states, the phase-space nonclassicality can be associated with quantum correlations, due to the fact that in a classical description of the joint system no such effects are present [3, 4].

Recently, Ferraro and Paris [5] showed that the two definitions of quantum correlations from quantum information and quantum optics are inequivalent. This means that every quantum state which is classically correlated with respect to the quantum information definition of quantum correlations is necessarily quantum correlated with respect to the quantum optical criteria and vice versa. One can also compare the operational differences between the two approaches. On one hand, the quantum correlations of quantum information have been shown to be necessary for specific nonlocal quantum communication and computation tasks to outperform their classical counterparts. On the other hand, however, quantum correlations in quantum optics lack such a nonlocal operational justification, i.e., there is no particular quantum information protocol which exploits phase-space nonclassicality to outperform a classical counterpart protocol.

In this paper, we introduce nonlocal BosonSampling as an intermediate model of quantum computing which is performed by distant agents (see Fig. 1) and use it to demonstrate the operational interpretation of phase-space nonclassicality in quantum informatics [6]. Specifically, we show that there exists a quantum state, namely a product of fully dephased two-mode squeezed vacuum states,

$$\begin{aligned}\hat{\varrho}_{\mathrm{AB}} &= \hat{\varrho}_i^{\otimes m}\\ &= (1-\epsilon^2)^m \sum_{j_1,\ldots,j_m=0}^{\infty} \epsilon^{2\sum_{k=1}^m j_k} \left(\bigotimes_{k=1}^m |j_k\rangle_{\mathrm{A}}\langle j_k|\right)\\ &\quad \otimes \left(\bigotimes_{k=1}^m |j_k\rangle_{\mathrm{B}}\langle j_k|\right),\end{aligned} \tag{1}$$

which is strictly classical (CC) with respect to entropic measures of correlations in quantum information allowing for efficient classical simulation of local statistics of two BosonSampler parties, Alice and Bob, in our protocol, which at the same time, prohibits efficient classical simulation of nonlocal correlations between the two. The only known resource present within the state (1), in contrast to the scatter-shot BosonSampling [7], is that of phase-space nonclassicality, as shown in [8]. Hence, we see that, nonlocal BosonSampling takes advantage of phase-space nonclassicality to perform a nonlocal task more efficiently than any classical algorithm.

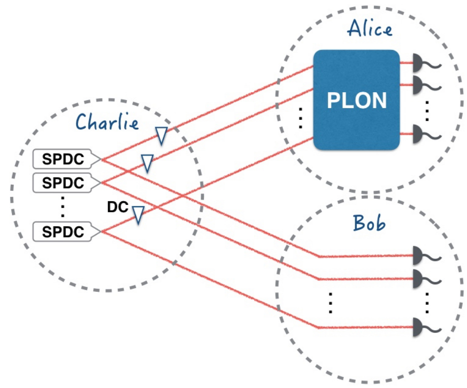

Figure 1: The schematic of a nonlocal BosonSampling protocol with CC input state. Charlie uses m SPDC sources and a series of dephasing channels (DC) to produce fully dephased two-mode squeezed vacuum states (FDTSV), and shares the final state between two spatially separated agents. Alice performs BosonSampling using a passive linear-optical network (PLON) and $\{0,1\}$ Fock basis measurements, while Bob only performs $\{0,1\}$ Fock basis measurements. We show that, Alice and Bob can efficiently simulate their local sample statistics classically. However, they cannot efficiently simulate the correlations between their outcomes using classical computers and any amount of classical communication, although there is no entanglement or discord between agents at any time.

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Electro-optic spectral manipulation driven by optical pulses

Filip Sośnicki, Michał Karpiński

Faculty of Physics, University of Warsaw

A promising approach to create large-scale, functional quantum information processing system is via a hybrid quantum network consisting of different quantum devices such as single photon sources, quantum memories or quantum gates interconnected with photonic links. This variety of quantum devices, as well as photonic links show disparate spectro-temporal properties, such as central wavelength or spectral bandwidth of single photons. The latter can vary from hundreds of GHz for spontaneous parametric down conversion (SPDC) sources of entangled (or heralded) photons, to single GHz linewidth of off-resonant quantum memories or channels widths of dense wavelength division multiplexed (DWDM) photonic links. Interfacing such systems creates a need to efficiently manipulate spectral bandwidth of single photons.

Bandwidth conversion can be explained on basis of optical space-time duality (OSTD) [1], which relates spectro-temporal optics concepts with their spatial analogues. Using OSTD one can postulate a time lens, which consists of applying time-varying quadratic phase on the optical pulse. The bandwidth converter (BC) consists then of a dispersive element followed by a temporal lens implemented by direct electro-optic phase modulator (EOPM) allowing for deterministic, low-loss, spectro-temporal manipulation, intrinsically free of noise [2].

A quadratic phase is usually obtained by driving an EOPM with a RF sine signal, such that its extremes, which approximate a quadratic phase, are synchronized with optical pulses. However such synchronization is technically challenging. Moreover the duty cycle of optical pulse is usually very small, but the RF signal is continuous. Only fraction of it modulates optical pulses, while the power is delivered to the system for the whole time, which generates large amounts of heat. Here instead of RF sine signal, we use a high-bandwidth photodiode driven by pulsed pump laser, which generate sub-ns RF wave packets with repetition rate of a pump laser, resulting in synchronous EOPM driving signal with modulated optical pulses [3]. This *natural* synchronization does not require additional phase-lock loops, simplifying the experimental setup, see Fig. 1(a). Moreover the electronic power is present in the system only when it is needed. It reduces heat generation, which enables higher instantaneous power, resulting in higher performance of a time lens and whole bandwidth converter.

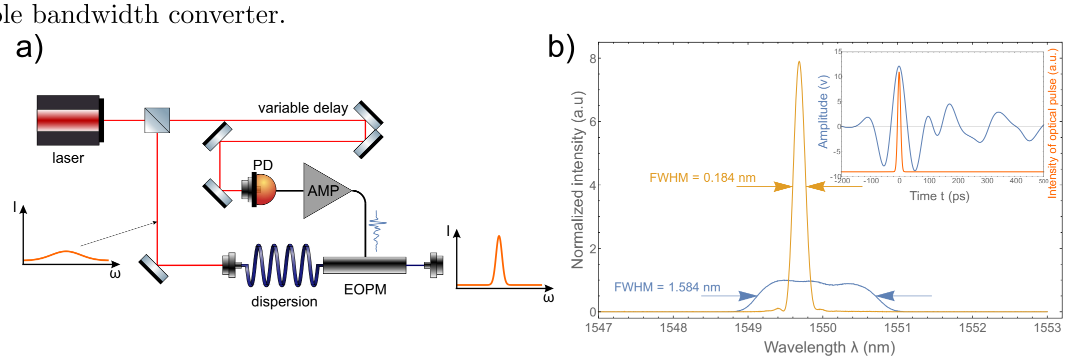

Figure 1: (a) Basic experimental setup of bandwidth converter (b) Spectral intensities of initial (blue) and spectrally compressed wavepackets (orange). The inset shows the electronic signal and a schematic representation indicating temporal intensity of a modulated pulse.

We have experimentally implemented a time lens using EOPM driven by amplified high-bandwidth photodiode. We used this setup to demonstrate a bandwidth conversion of weak coherent light by a factor exceeding 8. By changing delay between electronic signal and optical pulses we used it also to spectrally shear the optical pulses in range of 2 nm for coherent light as well as modify joint spectral intensity of photon pairs produced via SPDC process. Our results indicate that optically driven electro-optic converters may increase performance of hybrid quantum networks. Lower heat generation may also allow for its on-chip integration.

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Theory of coherent control with quantum light

***Frank Schlawin*[1]*, and Andreas Buchleitner*[2]**

[1] *Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*
[2] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany*

The nonlinear interaction between light and matter on a single atom/molecule and few-photon level is of great fundamental and practical interest. Clearly, the feeble probe and signal fields in such experiments pose a formidable challenge: In order to detect the typically very weak nonlinear effects at small photon numbers (on the order of one), one seeks to, either, optimize the nonlinearity of the optical medium, or to manipulate the light fields. In this talk, we theoretically investigate the latter route.

In particular, we examine a fundamental problem in quantum optics: What is the optimal pulse form to drive a two-photon-transition? While optimal pulse forms for single-photon transitions have already been described [1, 2], contradictory results have been published on two-photon transitions, and especially the possible role of photon entanglement [3, 4, 5].

In formulating this question as a coherent control problem, we show that - and quantify how much - the strong frequency quantum correlations of entangled photons enhance the transition compared to shaped classical pulses [6]. In ensembles of collectively driven two-level systems, such enhancement requires non-vanishing interactions. Incidentally, our results challenge commonly held beliefs in coherent control, according to which the quantum nature of light is detrimental, and open a new avenue for exploiting quantum correlations in the control of molecular processes.

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COMPLETE DESCRIPTION OF HIGH-GAIN TWIN-BEAM GENERATION VIA A CASCADED NONLINEARITY

[1] G. Triginer, [1] M.D. Vidrighin, [1] A. Eckstein, [2]N. Quesada, [3]W.S. Kolthammer, [1] I.A.Walmsley
[1] Department of Physics, University of Oxford, United Kingdom
[2]Xanadu, Toronto, Canada
[3]Department of Physics, Imperial College London, United Kingdom
e-mail: gil.triginergarces@physics.ox.ac.uk

Recent advances in the design of broadband parametric down-conversion (PDC) sources have opened the possibility to attain a regime of squeezing previously inaccessible in the pulsed domain [1]. However, characterising such twin-beam sources is a challenging task when multiple spectral modes are being squeezed simultaneously. Moreover, as one approaches the high squeezing regime, a number of nonlinear effects that are not usually considered at low pump power become relevant [2, 3].

We show that cascaded difference frequency generation (DFG) can be used to obtain a complete and self-referenced description of the quantum properties of light generated in a broadband twin beam source, even in the high gain regime. To do so, the frequency of a narrowband seed beam is scanned across the spectrum of one of the output fields and the resulting stimulated emission is collected. In contrast to previous stimulated emission tomography methods [4], we detect both the intensity generated via DFG in the unseeded mode as well as the light generated via cascaded DFG in the seeded mode. We show that these measurements enable a complete estimation of the Schmidt decomposition of the source, including the magnitude of the squeezing parameters, even in the presence of uncalibrated detection losses and mode overlap.

We demonstrate this method by characterizing characterizing nearly factorable parametric down conversion (PDC) in the high gain regime (up to mean photon number of 50) using a ppKTP waveguide. We show that our method provides a robust description of such sources even at high gain, revealing rich dynamics where not only PDC but also self-phase and cross-phase modulation play an important role. We fit our measurements to a theoretical model that incorporates these nonlinear phenomena, finding good agreement with the experimental data with a small number of fitting parameters. We discuss the implications of our findings on the viability of these sources for the generation of highly squeezed and spectrally single-mode quantum states.

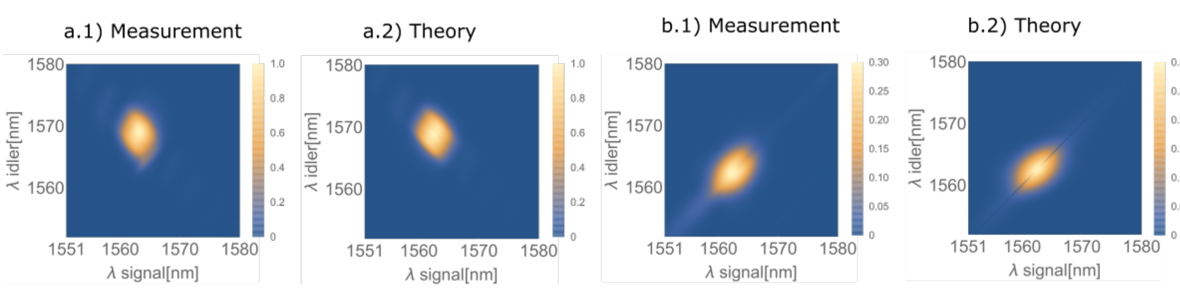

Fig 1. Comparison of experimental characterization to a theoretical model. The measurement and model are shown for a) direct DFG, b) cascaded DFG

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Quantum temporal imaging with squeezed light

G.Patera[1], D. B. Horoshko[1,2], J. Shi[1,3], and M. I. Kolobov[1]
[1]Laboratoire PhLAM, Université de Lille 1, 59655 Villeneuve d'Ascq, France
[2]B.I.Stepanov Institute of Physics, NASB, Nezavisimosti Ave. 68, Minsk 220072 Belarus
[3]University of Chinese Academy of Sciences, Beijing 100049, China

Temporal imaging is a technique enabling manipulation of temporal optical signals in a manner similar to manipulation of optical images in spatial domain. The concept of temporal imaging uses the notion of space-time duality [1] with dispersion phenomena playing the role of diffraction and quadratic phase modulation in time acting as a *time lens*.

Spatial quantum imaging investigates ultimate quantum limits of imaging techniques in regimes where quantum fluctuations cannot be neglected [2]. On one hand it would be desirable to bring the experience from spatial quantum imaging into temporal imaging and to establish its ultimate limits imposed by the quantum nature of the light. On the other hand the quantum description of temporal imaging is relevant in the context of long range quantum communication. Indeed this technology relies on the efficiency of quantum repeaters for which the temporal mode matching between the quantum emitters, the communication network and the quantum memories is critical.

In this work we address the problem of temporal imaging of a temporally broadband squeezed light generated by a traveling-wave optical parametric amplifier. We consider a single-lens temporal imaging system formed by two dispersive elements and a parametric temporal lens, based on non-linear processes such as sum-frequency generation [5,6] and four-wave mixing [7]. We derive a unitary transformation of the field operators performed by this kind of time lens and evaluate the squeezing spectrum at the output of the single-lens imaging system. When the efficiency factor of the temporal lens is smaller than unity, the vacuum fluctuations deteriorate squeezing at its output. For efficiency close to unity, when certain imaging conditions are satisfied, the squeezing spectrum at the output of the imaging system will be the same as that at the output of the OPA in terms of the *scaled frequency* $\Omega' = M\Omega$ which corresponds to the scaled time $t' = t/M$. The magnification factor M gives the possibility of matching the coherence time of the broadband squeezed light to the response time of the photodetector.

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Quantum-enhanced phase estimation with few-photon states

G. S. Thekkadath[1], R. Nichols[2], P. A. Knott[2], C. G. Wade[1], I. A. Walsmley[1]
[1]*Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK*
[2]*Centre for the Mathematics and Theoretical Physics of Quantum Non-Equilibrium Systems (CQNE), School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, UK*

In optical metrology it has long been known that quantum states of light can be engineered to surpass classical bounds on phase-sensitivity by exploiting non-classical correlations. However, such states are often difficult to prepare with large average photon-numbers. To this end, here we show how to generate a quantum state of light that is significantly more phase-sensitive than previously proposed states (e.g. N00N and squeezed-vacuum states), especially at low average photon-numbers ($\langle N \rangle \approx 1$).

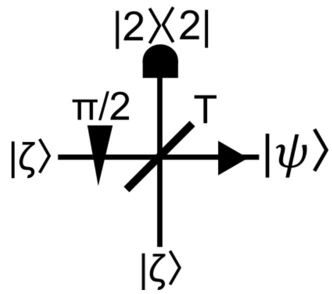

Fig. 1 : Scheme for generating the approximate squeezed Schrodinger cat state $|\psi\rangle$. There is a π/2 phase shift between the two squeezed vacuum states $|\zeta\rangle$.

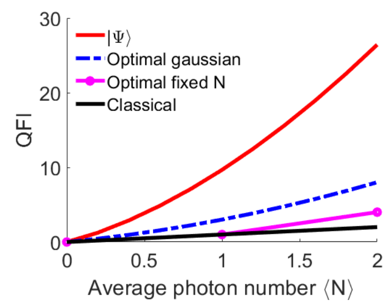

Fig. 2 : The state $|\Psi\rangle$ exhibits a large improvement in quantum Fisher information (QFI) compare to other existing states at low average photon numbers.

Our proposal draws from Ref. [1] which shows that squeezed Schrodinger cat states can exhibit a very large interferometric phase-sensitivity. Such cat states are non-Gaussian states that have a large variance in their photon-number distribution relative to their average photon-number, making them ideal for phase-sensing. Motivated by this, we consider the experimental scheme used in Ref. [2] to generate approximate squeezed Schrodinger cat states. The scheme is shown in Fig. 1 and works as follows: two squeezed vacuum states $|\zeta\rangle$ impinge onto a beam splitter (BS) of transmissivity T. At one output port of the BS, a photon-number resolving detector (PNRD) performs the heralding measurement $|2\rangle\langle 2|$. That is, the state of interest $|\psi\rangle$ is produced only when the PNRD counts two photons. In order to use the state for phase sensing, one would need to create two copies of $|\psi\rangle$: the first copy probes the phase shift ϕ while the second copy serves as a phase reference. The two copies then interfere on a BS to produce a final two-mode state $|\Psi\rangle$. The phase shift ϕ is estimated by projecting $|\Psi\rangle$ onto number states using a pair of PNRDs.

We optimize the transmissivity T and squeezing ζ to maximize the quantum Fisher information (QFI) of the state $|\Psi\rangle$ with respect to ϕ. The QFI quantifies the phase-sensitivity of $|\Psi\rangle$ maximized over all possible projective measurements (we note that PNRDs are an optimal projective measurement, i.e. saturate the Cramer-Rao bound [1]). The QFI of $|\Psi\rangle$ as a function of average photon number $\langle N \rangle$ is shown in Fig. 2. We also plot the QFI of other well-known states for comparison. The QFI of $|\Psi\rangle$ surpasses the QFI of the optimal fixed photon-number state, i.e. N^2. Similarly, it surpasses the QFI of the optimal Gaussian state, i.e. $\langle N \rangle^2 + 2\langle N \rangle$. In ongoing work we are investigating the scheme's robustness to preparation and detection losses as well as using machine learning to optimise the experimental setup. Ultimately we aim to implement a proof-of-principle demonstration.

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Broadband, noise tolerant optical switching devices inspired by composite pulses

Jacob F. F. Bulmer, Jonathan A. Jones, Ian A. Walmsley

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

In this work we present a new approach for designing integrated optical switches which have vastly improved tolerance to noise in their driving electronics. Our designs are inspired by composite pulses, a technique which was initially pioneered in the field of nuclear magnetic resonance (NMR) but has since been applied to a range of applications in quantum information processing to create high fidelity gates.

Fast, broadband optical switching with low crosstalk is important for a wide range of technologies [1], including proposals for linear optical quantum computers [2], where they are particularly useful for multiplexing probabilistic heralded processes to near unit success probability.

To map composite pulses from NMR to photonics, we go via the spatial dual-rail qubit: a single photon within two orthogonal spatial modes, typically a pair of single mode waveguides. An ideal 2×2 switch can be thought of as acting as either the identity or Pauli X single qubit gates on these two modes. A common implementation uses a Mach-Zehnder interferometer (MZI) which works by having an active phase modulator between a pair of balanced directional couplers. The phase modulator can apply variable Z rotations and the couplers apply fixed X rotations to the qubit.

We use this connection to qubit gates to propose new designs for 2×2 optical switches which are broadband and tolerant to noise in their control signals. This noise tolerance not only protects against errors in routing the light through the switch, but uniquely it also protects the phase information. The two designs presented here are inspired by the composite pulses known as the Tycko [3] and PB1 [4] composite NOT gates. In fig. 1 we compare our designs to a conventional MZI based switch.

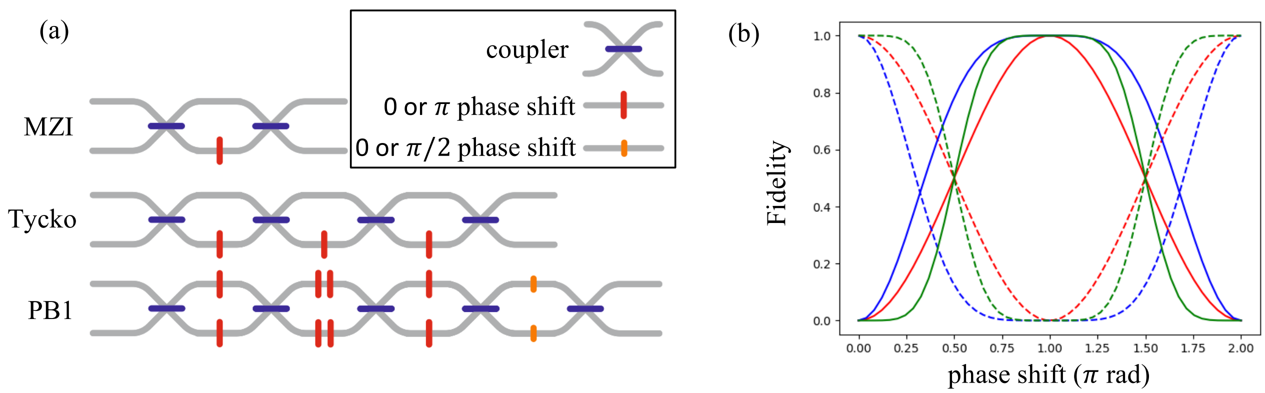

Figure 1: (a) Physical layout of the Tycko and PB1 switches in comparison to an MZI. For clarity, fixed phase shifts and coupling ratios are not displayed. (b) Fidelity of the MZI, Tycko and PB1 (red, blue, green) switch transformation against identity (solid) and Pauli X (dashed) as a function of phase. We assume all the phase shifters are driven with the same control signal and, as such, their phases are correlated. PB1 provides tolerance to variations in phase at both 0 and π phase shift and so we suggest an implementation using *push-pull* to halve the required optical depth of the modulators.

There are many other composite pulse sequences which we plan to investigate that we think will have promising applications in switching as well as other areas of integrated photonics, such as wavelength demultiplexing and filtering. We also plan to investigate using tuning strategies [5] to correct for fabrication errors in these devices.

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Characteristics of nanostructural beam splitter

Jakub Szlachetka*[1], **Karolina Słowik**[1], **Piotr Kolenderski** [1]
1. Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Toruń, Poland

Photons produced in the SPDC process typically propagate through optical elements such as waveguides, lenses and beam splitters. We aim to exploit unconventional optical elements, whose fabrication has recently become possible due to the rapid development of nanotechnologies. Such miniaturized devices are typically integrated on microchips that may later become parts of larger quantum circuits. An example is provided by metamaterials, which are periodic arrays of metallic nanoparticles. These nanoparticles support surface plasmon polaritons - hybrid excitations that combine electromagnetic fields with coherent oscillations of valence-electron plasma. Here we experimentally characterize a nanostructural beam splitter, which was designed to feature 25 % of reflection and transmission, and 50 % of absorption.

*Corresponding author: jakubuch@gmail.com

Towards practical multi-colour nonlinear mixing devices

Jano Gil Lopez, Matteo Santandrea, Nicola Montaut, John Donohue, Vahid Ansari, Markus Allgaier, Harald Herrmann, Raimund Ricken, and Christine Silberhorn
Universität Paderborn, Integrierte Quantenoptik, Warburger Str. 100, D-33098

Nonlinear wave-mixing allows for frequency conversion, bandwidth manipulation and temporal mode selective operations such as Quantum Pulse Gates (QPGs). Such processes have many applications in photonic networks, both classical and quantum. These processes can be engineered in integrated optical devices in nonlinear materials to increase the efficiency, ease the alignment and reduce the footprint.

The conditions needed for single-mode waveguiding vary drastically between different wavelengths. To support all the fields interacting simultaneously in wave-mixing processes, significant engineering is required. Waveguide inhomogeneities and fabrication defects, which degrade the process fidelity, must also be surpassed. To overcome these issues and increase the efficiencies we investigate the use of on-chip tapers, bendings and dichroic couplers in Lithium Niobate waveguides.

The goal is to produce efficient integrated wave-mixing devices (with a focus on QPGs), reducing the footprint and the need for bulk optics while allowing for complex interactions and processes.

Phase Sensitive Amplification Assisted by Coherent Population trapping

J. Lugani[1], C. Banerjee[2], M-A. Maynard[2], P. Neveu[2], R. Ghosh[3], F. Bretenaker[2], E. Brion and F. Goldfarb[2]

[1]*Clarendon Laboratory, Department of Physics, University of Oxford, Oxford, OX1 3PU, UK*
[2]*Laboratoire Aime Cotton, CNRS - Universite Paris Sud 11 - ENS Cachan - Universite Paris-Saclay, 91405 Orsay Cedex, France*
[2]*Shiv Nadar University Gautam Buddha Nagar, UP 201314, India*

Optical parametric amplification has been a widely studied phenomenon in optics, owing to its unique noise properties. Specifically, phase sensitive amplification (PSA) is interesting as it allows for amplification of a weak signal without degrading its signal to noise ratio (SNR) and is also associated with the generation of non-classical (squeezed) states of light [1]. PSA has been extensively implemented in non-linear crystals using three wave mixing [1] and in fibers [2] and atomic vapours [3,4] using four wave mixing.

In the present work, we implement PSA in metastable helium vapours at room temperature [4]. We exploit the simple level structure of helium 4 (see fig. 1 a,b,c): the D_1 transition, because of selection rules, constitutes a well defined closed lambda system, allowing for a strong coherent population trapping (CPT) effect to occur. Moreover, two other transitions share the same ground states, which can be fully exploited to have multiphoton nonlinear processes that explicitly address the dark and the bright state. Therefore, we expect this atom to exhibit a strong nonlinear third-order susceptibility while being free from absorption.

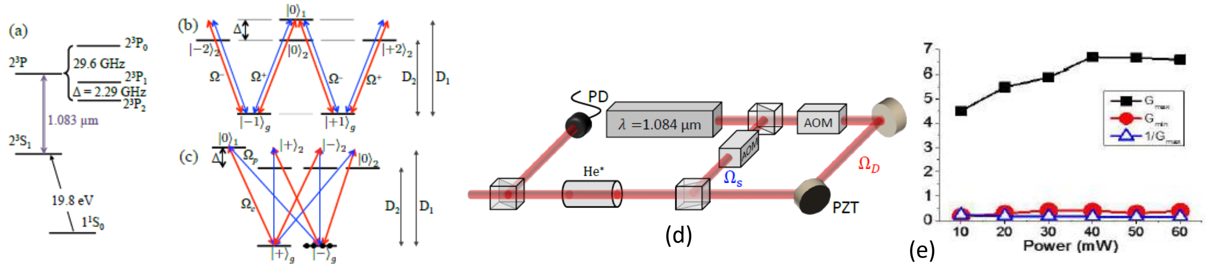

Fig. 1 (a) Level scheme in helium 4. The D_1 transition is resonantly excited, while the D_2 transition is far detuned, (b) excitation schemes are shown in the atomic basis B_{at} and (c) in the dark and bright states basis B_s defined by the coupling field, (d) schematic of the experimental set up: Pump, signal and idler derived from the same laser have their frequencies and amplitudes controlled by two acousto-optics (AO). A polarizing beamsplitter (PBS) recombines the beams before the cell. The piezo-actuator in the pump path enables to scan the relative phase, (e) Variation of the maximum and minimum PSA gain as a function of the optical power.

Using this scheme, we could achieve a maximum gain of nearly 7 for the pump power of 50 mW. Fig. 1d shows the schematic of the experimental set up and fig. 1e plots the variation of maximum and minimum gain (G_{max} and G_{min}) as a function of pump power. The measured gains correspond well with each other ($G_{min}=1/G_{max}$, ideally), illustrating a pure PSA. This should be related to the generation of highly squeezed states of light, which could be used for light storage experiments in metastable helium and other applications in quantum information.

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Direct characterization of ultrafast energy-time entangled photon pairs

Jean-Philippe W. MacLean[1,2], John M. Donohue[1,2,3], K.J. Resch[1,2]

[1] Institute of Quantum Computing, University of Waterloo, Waterloo, Canada, N2L 3G1
[2] Department of Physics and Astronomy, University of Waterloo, Waterloo, Canada, N2L 3G1
[3] Integrated Quantum Optics, Applied Physics, University of Paderborn, 33098 Paderborn, Germany
jpmaclean@uwaterloo.ca

***Abstract*—We implement ultrafast photon counters based on nonlinear interactions and strong femtosecond laser pulses to probe energy-time entanglement in the ultrafast regime. Using this technique and single-photon spectrometers, we characterize all the spectral and temporal correlations of two entangled photons with femtosecond resolution. This enables the witnessing of energy-time entanglement using uncertainty relations and the direct observation of nonlocal dispersion cancellation on ultrafast time scales. These techniques are essential to understand and control the energy-time degree of freedom of light for ultrafast quantum optics.**

Keywords—Entanglement detection, quantum entanglement, nonlinear optics, quantum optics, ultrafast phenomena

Energy-time entangled photons are critical in many quantum optical phenomena and have emerged as important elements in quantum information protocols. The energy-time degree of freedom supports various encodings, including frequency bins, time bins, and broadband temporal modes, and is intrinsically robust for propagation through long-distance fiber links. Applications which harness quantum correlations in this degree of freedom, referred to as energy-time entanglement, include dispersion cancellation, high-dimensional quantum key distribution, and quantum-enhanced clock synchronization.

Entanglement in this degree of freedom often manifests itself on ultrafast time scales, making it very difficult to detect, whether one employs direct or interferometric techniques, as photon-counting detectors have insufficient time resolution. In nonlinear optics and laser physics, optical gating is widely used to overcome limitations with detectors which are too slow to observe features on sub-picosecond time scales. The gating is achieved by combining the signal with a short gate pulse in a nonlinear medium and measuring the up-conversion signal on the detector. With fast gates and slow detectors, an effective fast detector can be engineered to temporally resolve single photons and photon pairs.

In this work, we develop fast optical gating to achieve sub-picosecond timing resolution for spatially separated pairs of single photons. We use this technique in conjunction with single-photon spectrometers to explicitly measure both the spectral and temporal correlations of broadband photons, as well as the cross-correlations between the frequency of one photon and the time of arrival of the other. Furthermore, by controlling the dispersion of each photon, our high-resolution joint temporal measurements make it possible to directly observe nonlocal dispersion cancellation on femtosecond time scales.

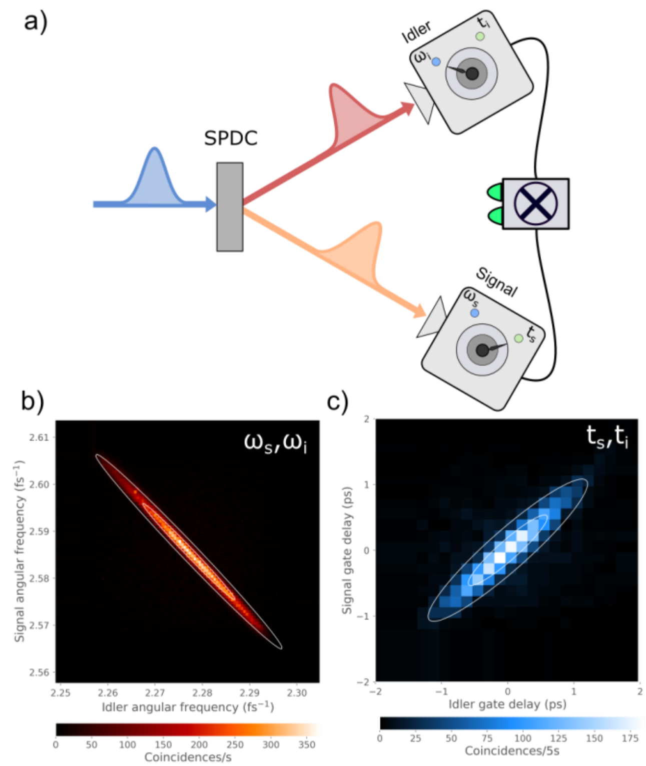

Fig 1. (a) Frequency-entangled photons are created through spontaneous parametric down-conversion of an ultrafast pulse from a frequency-doubled Ti:sapphire laser. Measurements of either the frequency or the time of arrival of each photon can be performed in coincidence. (b,c) A combination of spectral and temporal measurements are made in coincidence in order to measure (b) the joint spectrum and (c) the joint temporal intensity. Spectral measurements are made with dual single-photon monochromators. Time resolved single photon detection is achieved with sum frequency generation and we control the dispersion of the individual photons with a grating compressor.

We directly observe energy time entanglement of the ultrafast biphotons from the strong frequency anti-correlations between photons as well as the strong positive correlations in photon arrival times, measuring an energy time uncertainty product, $\Delta(\omega_1 + \omega_2)\Delta(t_2 - t_1) = 0.290 \pm 0.007$, well below the classical limit of 1[1]. The experimental apparatus developed here provides a direct way to detect energy-time entanglement in a regime inaccessible to current detectors.

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Limitations to the sensitivity of a three-mode nonlinear interferometer

Jefferson Flórez, Davor Curic, Lambert Giner, Enno Giese, Jeff S. Lundeen
Department of Physics and Centre for Research in Photonics,
University of Ottawa, 25 Templeton Street, Ottawa, Ontario K1N 6N5, Canada
Email: jflor020@uottawa.ca

***Abstract*—We investigate the phase sensitivity of a nonlinear interferometer. Unlike previous analyses, we take into account the quantum features of the pump field. After obtaining the quantum state that describes the pump, signal and idler modes at the interferometer output, we calculate the phase uncertainty by means of the classical Fisher information. We compare this uncertainty with the one predicted in the parametric approximation, which allows us to establish the range of validity for such an approximation. We finally study the minimum phase uncertainty as a function of the input number of pump photons, and find an inverse scaling with this number, which is also known as Heisenberg scaling.**

***Keywords*—Quantum metrology, Phase sensitivity, Nonlinear interferometer.**

Nonlinear interferometers (NLIs) are phase-sensitive measurement devices that rely on active optical elements such as parametric amplifiers or four-wave mixers [1]. NLIs are of particular interest since the phase sensitivity scales with the number of photons inside the interferometer, which is usually called Heisenberg scaling [2]. However, to the best of our knowledge, the quantum features of the pump have been ignored within the so called parametric approximation. In this contribution, we explore the limitations of the phase sensitivity beyond the parametric approximation and discuss whether a Heisenberg scaling can still be achieved.

We consider an unseeded, nondegenerate and balanced NLI, like the one shown in Fig. 1, which is pumped by a coherent state $|\alpha_p\rangle$. The interaction between the pump and the generated photons after the second nonlinear crystal (crystal B in Fig. 1) is phase sensitive and the quantum state at the output face of the interferometer depends on the relative phase $\phi = \phi_p - \phi_s - \phi_i$.

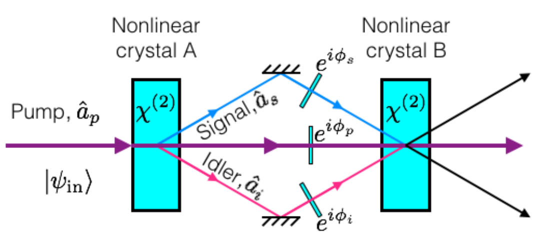

Fig. 1: Schematic representation of a nonlinear interferometer.

By numerically diagonalizing the interaction Hamiltonian between the three optical modes interacting in the NLI [3], we obtain the phase sensitivity $\Delta\phi_{CF}$ through the classical Fisher (CF) information based on the number of output signal or idler photons. In Fig. 2(a) we plot $\Delta\phi_{CF}$ as a function of the normalized time $\tau = \kappa t$, where κ is the parametric gain and t is the interaction time in each crystal. For comparison, we also plot the phase uncertainty $\Delta\phi_{PA}$ obtained by means of the parametric approximation (PA). We conclude from Fig. 2(a) that $\Delta\phi_{CF}$ and $\Delta\phi_{PA}$ are exactly the same in the short time regime, given by $\tau < |\alpha_p|^{-1}$. In contrast, the parametric approximation overestimates the phase uncertainty for longer normalized times ($\tau > |\alpha_p|^{-1}$), while including the quantum pump field leads to an oscillatory behavior.

This work was supported by the Canada Research Chairs (CRC) Program, the Natural Sciences and Engineering Research Council (NSERC), and the Cananda Excellence Research Chairs (CERC) Program. JF acknowledges support from COLCIENCIAS.

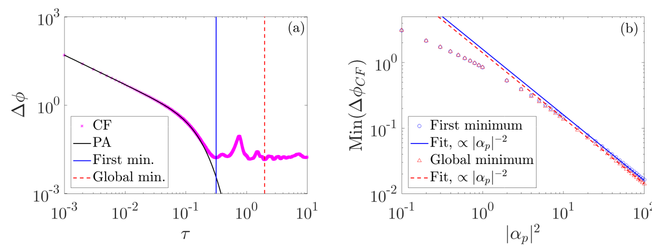

Fig. 2: (a) Phase uncertainty as a function of the normalized time for $|\alpha_p|^2 = 100$. (b) Global and first minimum of $\Delta\phi_{CF}$ as a function of the input number of pump photons. The fitting has been done for $10 \leq |\alpha_p|^2 \leq 100$.

We mark the global and first minimum of the phase uncertainty by vertical blue and red lines in Fig. 2(a). When we calculate $\Delta\phi_{CF}$ for different $|\alpha_p|^2$ values, we obtain a set of these minima, which are in Fig. 2(b). When $|\alpha_p|^2 \gg 1$ we see that the minimal phase uncertainty for both the global and first minimum scales with the inverse of the number of *input* photons, i.e. $|\alpha_p|^{-2}$, which can be seen as a Heisenberg scaling. This is in contrast to the conventional NLI based on the parametric approximation, also known as SU(1,1) interferometers in the literature, where the Heisenberg scaling is with respect to the number of *generated* photons inside the interferometer [4]. We show that even for coherent input states and pump depletion, the interferometer still has supersensitive properties. We extend in this way the current phase sensitivity description of NLIs beyond the parametric approximation, finding a Heisenberg scaling with the number of pump photons.

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