

# Annual Report 2011

## Measurement and Information in Optics

MSM 6198959213

and

## Center of Modern Optics

LC06007

The Annual Report 2011 covers all the scientific activities achieved in the long-term projects supported by the Czech Ministry of Education MSM 6198959213 **Measurement and Information in Optics MIO 2005 - 2011** and LC06007 **Center of Modern Optics CMO 2006 - 2011**. As traditionally all the results and activities of individual small teams are described comprehensively on a single page. This shows the progress of our research in the fields of modern optics and quantum information processing in the current year.

Olomouc, January 2011

Zdeněk Hradil  
coordinator of the project MSM6198959213

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## Experimental quantum information processing

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In 2011 we have successfully finished four experiments on quantum information processing in our new quantum optics laboratory and we participated in one experiment performed at ICFO in Spain.

We have used fast electronic feed-forward to increase the success probability of a linear-optical programmable phase gate from 25% to its theoretical limit of 50% [1]. The feed-forward applies a conditional unitary operation which corrects the output states of the data qubit. The gate itself rotates an arbitrary quantum state of the data qubit around the  $z$ -axis of the Bloch sphere with the angle of rotation being fully determined by the state of the program qubit. The gate implementation is based on fiber optics components. We have verified the increase of the probability of success and characterized the gate by means of quantum process tomography. We have demonstrated that the use of feed-forward affects neither the process fidelity nor the output-state fidelities.

Further we dealt with the optimal strategy for the minimum-energy unambiguous quantum reading of optical memories where the information is stored as the reflectivity of the memory cells [2]. To demonstrate the experimental feasibility of quantum reading we have built a laboratory set up for perfect discrimination of two beam splitters with different reflectivities. It consists of a Mach-Zehnder interferometer with an additional beam splitter in its upper arm. This additional beam splitter has a variable splitting ratio and it serves as a device to be discriminated. It is a superposition of a single photon and vacuum what is entering this device, so the device is exposed only to a fraction of the energy of a single photon on average.

We have verified experimentally quantum non-Gaussian character of single-photon-like states with positive Wigner

functions generated by our heralded photon source [3]. I.e., we have demonstrated that these states cannot be expressed as mixtures of Gaussian states. We have also investigated the influence of background noise on the properties of the output states. Sufficient information to witness the quantum non-Gaussian character can be obtained from a standard photon anti-correlation measurement. In comparison to the witness based on negativity of the Wigner function, this criterion can identify non-classicality of a much wider class of single-photon sources, while avoiding the need for estimation of complete photon-number distribution.

We have experimentally demonstrated a protocol for conditional noiseless suppression of losses in quantum optical channels using quantum filters at the input and output of the channel [4]. In particular, we used the process called noiseless attenuation in combination with noiseless amplification, which enables the conditional suppression of losses to an arbitrary extent without adding noise, hence keeping quantum coherence. An interesting feature of this scheme is that the closer to vacuum the encoded state sent through the channel is the more precisely the original state is reconstructed at the output.

A concept of dimension witnesses allows bounding the dimension of an unknown quantum system only from measurement statistics. We have participated in the experiment in Barcelona which has experimentally demonstrated the use of a dimension witnesses in a prepare and measure scenario [5]. It employed photon pairs entangled in polarization and orbital angular momentum to generate quantum states of dimensions up to four. The dimension witness was then used to certify their dimensionality.

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# Spiral incoherent correlation microscopy operating in 3D vortex reconstruction mode

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One of the research activities of the project is the correlation imaging, which combines principles of optical and digital holography with phase modulation implemented by a spatial light modulator (SLM). This is an original method that allows to realize holographic correlation recordings of the object in a one-way interferometer using quasi-monochromatic spatially incoherent light.

Our latest experimental results are based on previously proposed computational model [1] and represent a significant contribution to development of the method in terms of both new principles and applications. Correlation recordings of the object and their subsequent numerical reconstruction provide some specific features not available in common optical imaging. One of them is the image reconstruction with a resolution of details that exceeds the diffraction limit of collimating optics used in the experiment. This effect was studied theoretically and subsequently verified experimentally. In a good agreement with prediction, the image reconstruction with resolution that exceeds  $\sqrt{2}$  times the diffraction limit of used optics was demonstrated.

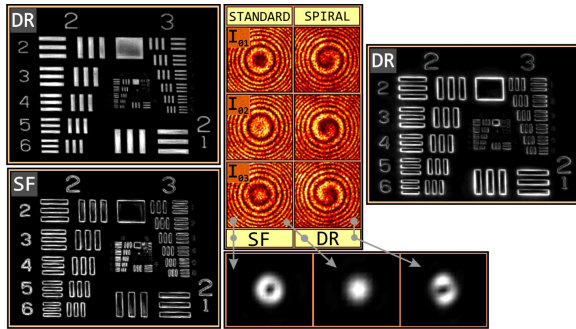


FIG. 1: Negative USAF test reconstructed by standard and spiral techniques from correlation records acquired with incoherent light. Middle part: standard and spiral recordings of a point source - vortex imaging is indicated by annular image spots.

Significant results were also obtained when studying an influence of the partial temporal coherence of light on the quality of reconstructed image. Due to the specific properties of the SLM and a variability of computer generated holograms that control its operation, experimental conditions were found in which the correlation recordings can be made even if the light with an extreme bandwidth of the spectrum is used. In the optimal geometry, the optical path difference of interfering waves was minimized to a few micrometers and the specimen recorded in white

light emitted by a halogen lamp was successfully reconstructed. This experiment is promising for applications of the method in fluorescence microscopy.

As the main result of our research, a new principle of vortex image reconstruction was proposed and experimentally verified [2]. A switching to vortex imaging mode was achieved by modifying the configuration of the experiment, in which the correlation records were implemented using helical reference waves. The vortex imaging can also be done using standard records when a spiral phase filtering is applied during reconstruction. As a result, the selective edge contrast enhancement is achieved (see Fig. 1), which is analogous to the optical spiral phase contrast imaging demonstrated in coherent light. Our experiment represents the first method that allows edge enhancement with incoherent light. The originality of the method is also in a possibility of creating the 3D images reconstructed numerically.

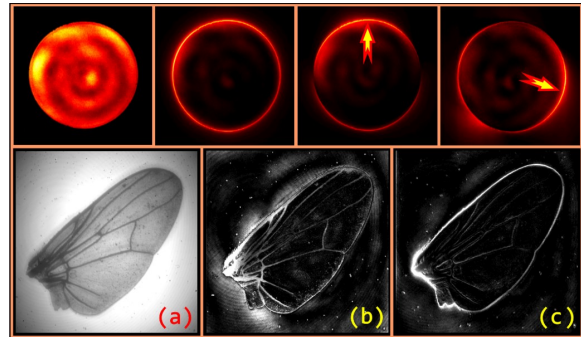


FIG. 2: Optical imaging and correlation reconstruction of a pinhole and a fly wing. Top row from left to right: direct optical imaging, isotropic spiral reconstruction, anisotropic spiral reconstruction with the selection of preferred directions. Bottom row: (a) direct optical image, (b) standard reconstruction and (c) isotropic spiral reconstruction.

In addition to the digital incoherent image reconstruction, the coherent optical spiral imaging was also examined. As the main result, a quantization of the spiral phase was studied as an effective tool for generation of fields with the nonzero orbital angular momentum. In imaging this effect results in a defocusing induced rotation of the point spread function (PSF), which can be utilized for an accurate localization of molecules in microscopy [3].

This work was supported by the Research Project of the Czech Ministry of Education Measurement and Information in Optics MSM 6198959213.

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# Non-classicality, information extraction and decoherence of single photon states

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We investigated a novel criterion of higher-order non-classicality of single photon non-Gaussian states of light [1], presented a novel analysis of decoherence and information accumulation for quantum compatible measurements [2] and studied a basic decoherence effect caused by a single photon [3].

We proposed a criterion giving a sufficient condition for quantum states of a harmonic oscillator not to be expressible as a convex mixture of Gaussian states. This nontrivial property is inherent to, e.g., a single-photon state and the criterion thus allows one to reveal a signature of the state even in quantum states with a positive Wigner function. The criterion relies on directly measurable photon number probabilities and enables detection of this manifestation of a single-photon state in quantum states produced by solid-state single-photon sources in a weak coupling regime. This theoretical analysis was a basement for experimental demonstration of such the higher-order non-classicality by our experimental group at the Department of Optics.

We compared a trade-off between knowledge and decoherence for the incoherent and coherent partial sequential compatible measurements on single-qubit systems. The individual partial measurement nondestructively monitors basis states of the system by single-qubit meter. For the same decoherence caused by this unbiased measurement, the individual coherent measurement gives more knowledge than the incoherent one. For identical sequential coherent measurements, knowledge accumulated not additively increases more slowly than for the incoherent measurements. The overall knowledge can be accumulated using an adaptive measurement strategy on the meters if the single-qubit coherence of meters is kept. On the other hand, preservation of the mutual qubit coherence between the meters necessary for the collective measurement strategy is not required. Since the decoherence caused by the measurement process is a quadratic function of knowledge extracted by the individual measurement, Zeno-like behavior can be observed for repetitive weak compatible measurements. In a collaboration with our group, these theoretical predictions have been recently experimentally investigated by a group at Sapienza University, Roma (Italy).

We investigated how the distinguishability of a noise

particle degrades interference of the signal particle. The signal, represented by an equatorial state of a photonic qubit, is mixed with noise, represented by another photonic qubit, via linear coupling on a beam splitter. We reported on the degradation of the signal photon interference depending on the degree of indistinguishability between the signal and noise photons. When the pho-

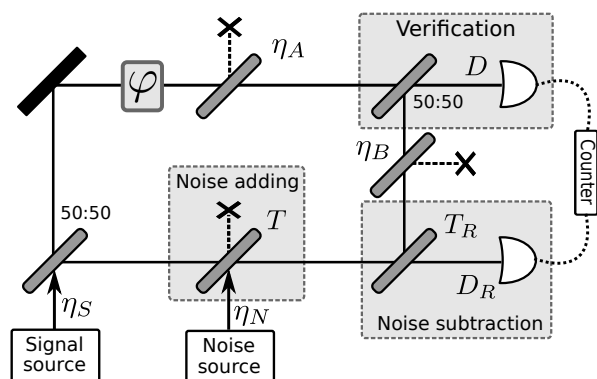


FIG. 1: Experiment to test a decoherence by single photon.

tons are completely distinguishable in principle but technically indistinguishable, the visibility drops to the value  $\frac{1}{\sqrt{2}}$ . As the photons become more indistinguishable, the maximal visibility increases and reaches the unit value for completely indistinguishable photons. We examined this effect experimentally using a setup with a fiber-optics two-photon Mach-Zehnder interferometer in a collaboration with the experimental groups at the Department of Optics and Laboratory of Science in Olomouc.

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# Applications of continuous-variable non-classical states of light

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We investigated a novel applications of squeezed Gaussian states for a construction of optimal quantum amplifier [1], for quantum key distribution with limited reconciliation efficiency [2] and proposed a scheme to generate squeezed three photon state as a key resource of weak quantum cubic interaction [3].

In a collaboration with the Tokyo University, we experimentally demonstrated phase-insensitive linear amplification of a continuous variable system in the optical regime, preserving the ancilla system at the output. Since our amplification operation is unitary up to small excess noise, it is reversible beyond the classical limit. In addition, combining this amplifier with a beamsplitter, we also demonstrated approximate cloning of coherent states where an anticloning is present. We investigated the reversibility by reconstructing the initial state from the output correlations, and the results are slightly beyond the cloning limit. Our amplifier is based on linear optics, offline-prepared additional ancillas in nonclassical states, and homodyne measurements followed by feedforward. Squeezed states are used as the additional ancillas, and nonlinear optical effects are exploited only for their generation.

We proposed a deterministic implementation of weak cubic nonlinearity, which is a basic building block of a full-scale continuous-variable quantum computation. Our proposal relies on preparation of a specific ancillary state and transferring its nonlinear properties onto the desired target by means of deterministic Gaussian operations and feed forward. We show that, despite the imperfections arising from the deterministic nature of the operation, the weak quantum nonlinearity can be implemented and verified with the current level of technology. A key resource is a designed superposition of Fock states of light up to three photons, which brings highly nonclassical behaviour necessary for the deterministic cubic interaction. This proposal has been recently experimentally verified by a group at the Tokyo University.

We addressed the security of continuous-variable quantum key distribution with squeezed states upon the realistic conditions of noisy and lossy environment and limited reconciliation efficiency. Considering the generalized

preparation scheme and clearly distinguishing between classical and quantum resources, we investigated the effect of finite squeezing on the tolerance of the protocol to untrusted channel noise. For a long-distance strongly attenuating channel and the consequent low reconciliation efficiency, we showed that feasible limited squeezing is surprisingly sufficient to provide the security of Gaussian quantum key distribution in the presence of untrusted noise. We explained the effect by the behaviour of the

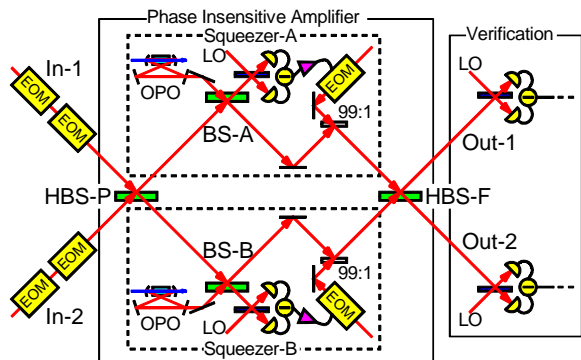


FIG. 1: Experimental implementation of complete scheme for optimal quantum amplification.

Holevo quantity, which describes the information leakage and is effectively minimized by the squeezed states. Recently, this proposal has been experimentally tested by a group at the Technical University of Denmark.

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# High-fidelity noiseless amplification and entanglement concentration via photon addition and subtraction

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The quantum noise associated to linear phase-insensitive amplifiers can only be avoided by relaxing the requirement of a deterministic operation. We have experimentally realized a probabilistic noiseless linear amplifier that is able to amplify coherent states at the highest level of effective gain and final state fidelity ever reached [1]. Based on a sequence of photon addition and subtraction [2, 3], and characterized by a significant amplification and low distortions, this high-fidelity amplification scheme may become an essential tool for quantum communications and metrology.

The implemented conditional noiseless amplifier has nominal gain  $g = 2$  and is mathematically described by an operator  $\hat{G} = \hat{a}\hat{a}^\dagger = \hat{n} + 1$ . Here  $\hat{a}$  ( $\hat{a}^\dagger$ ) denotes annihilation (creation) operator and  $\hat{n}$  is the photon number operator. The noiseless amplification thus operates by modulating the amplitudes of Fock states,  $\hat{G}|n\rangle = (n+1)|n\rangle$ .

The experimental setup is shown in Fig. 1. The addition of a single photon to an arbitrary light state is obtained by conditional stimulated parametric down-conversion in a nonlinear crystal. The photon addition in the output signal mode is heralded by the detection (by an on/off photodetector Da) of a single photon in the idler down-conversion channel. Single-photon subtraction is implemented by conditionally attenuating a state by detecting (by an on/off photodetector Ds) a single photon reflected from a high-transmissivity beam-

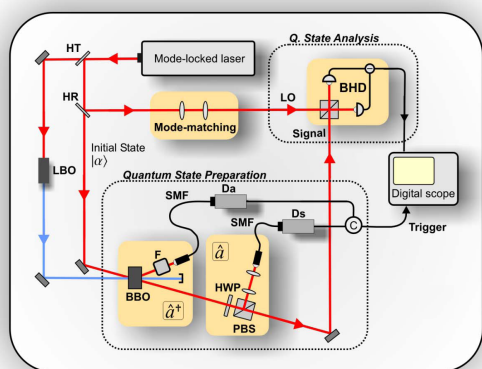


FIG. 1: High-fidelity noiseless amplification of light.

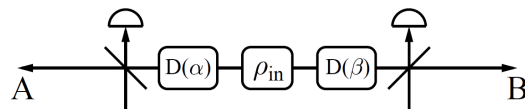


FIG. 2: Entanglement concentration by local displacements and photon subtractions.

splitter. Noiseless amplification is heralded by coincident detections from Da and Ds. The low parametric gain and the low reflectivity of beam-splitter (set to about 5%) guarantee that the experimental scheme is a very faithful implementation of the ideal operator sequence  $\hat{a}\hat{a}^\dagger$ .

Quality of experimental noiseless amplification of weak coherent states  $|\alpha\rangle$  with amplitude  $|\alpha| \lesssim 1$  was quantified by determining the effective gain and added noise of the amplifier. The measurements confirmed that the amplifier adds only very little noise while achieving a gain substantially higher than 1 for the whole range of considered amplitudes  $\alpha$ .

As a second application of the photon subtraction we have investigated the entanglement concentration of continuous-variable Gaussian states and we have shown that the performance of the protocol can be significantly improved if the local single-photon subtractions are combined with local coherent displacements [4], see Fig. 2. This procedure allows to conditionally extract one e-bit of entanglement even from a very weakly squeezed two-mode squeezed vacuum state. This is due to a destructive quantum interference that eliminates the otherwise dominant separable vacuum term.

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# Knowledge, ignorance and uncertainties in quantum tomography

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The team at Palacky University was involved in the broad international collaboration focussing at several research topics. In the collaboration with the colleagues from Singapore reconstruction with tomographically incomplete data was considered as the so called MaxLik MaxEnt (MLME) reconstruction. In these cases MaxLik tomography itself will not typically yield a unique result. In Ref. [1] we have derived a novel reconstruction scheme, where both the likelihood and von Neumann entropy functionals are maximized in order to systematically select the most-likely estimator with the highest entropy. Such a solution is the least-biased one based on a given set of measurement data. This is equivalent to a non-trivial utilization of partial knowledge and ignorance about the reconstructed state. The algorithm is robust and free of artifact associated with the cut-off in the parameters space. The method was illustrated on the numerical simulation with homodyne detection where the reconstruction on smaller space may lead to faked non-classical behavior whereas the MLME will tend to the correct value of the Wigner function at the origin of the phase space. This scheme was further extended for adaptive schemes and reconstruction of processes [2]. A detailed and comprehensive account of quantum state estimation by joint maximization of the likelihood and the entropy was published in [4]. After establishing the algorithms for both perfect and imperfect measurements, we applied the procedure to data from simulated and actual experiments from quantum information and optics

including Shack-Hartmann detection of the wave-front.

The ongoing research on quantization of angular momentum continued and the results related to phase space representation of angular momentum states was published in Ref. [3]. A comprehensive theory of the Weyl-Wigner formalism for the canonical pair angle-angular momentum was presented here. Special attention is paid to the problems linked to rotational periodicity and angular-momentum discreteness.

The collaborating members of the working group have met on two important meetings: The Heraus Summer School Modern Statistical Methods in Quantum Information Processing Bad Honnef, Germany (August 2011) and the Workshop on Quantum Tomography 2011, Singapore in (December 2011). These events have triggered further extensive collaboration on the topic related to quantum tomography. Continuation of the series of the quantum tomography workshops is scheduled on the year 2013 ( will be held preliminarily in Fields Institute, Toronto, Canada) with significant contribution of the team from Palacky University. Besides this several contributions are prepared for the special issue of New Journal of Physics devoted to the problems of quantum tomography, see the Ref. [5] and other contributions.

This work was supported by the Research Project of the Czech Ministry of Education "Measurement and Information in Optics" MSM 6198959213 and EU project COVAQIAL FP6- 511004.

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## Non-classical correlations for continuous variables

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Correlated states of composite quantum systems may exhibit non-classical features even if they are separable. They can possess, e.g., a nonzero quantum discord [1] being a difference of quantum generalizations of two classically equivalent expressions for mutual information. Quantum discord is endowed with operational interpretation [2] and it can also play the role of a resource of speed up in some mixed-state models of quantum computing [3]. Its evaluation, however, requires nontrivial optimization of a mean von Neumann entropy over all local measurements performed on one subsystem of a bipartite system. Although a closed analytical formula is missing even for two qubits one can get it for two-mode Gaussian states and Gaussian measurements [4].

In Ref. [5] we complemented the analysis of Ref. [4] by investigating for Gaussian states another quantifier of non-classical correlations known as measurement-induced disturbance (MID) and its ameliorated version (AMID) [6], which is an upper bound on discord. For a quantum state  $\rho_{AB}$  MID is defined as the difference of a quantum mutual information and a classical mutual information of the joint probability distribution of outcomes of measurements  $\Pi_A$  and  $\Pi_B$  in local eigenbases of  $\rho_{AB}$ . AMID is an optimized version of MID, where the latter quantity is maximized over all local measurements  $\Pi_A$  and  $\Pi_B$ . We have shown [5] that restricting to Gaussian states and measurements AMID can be determined analytically for pure states, squeezed thermal states and symmetrical states, whereas we have to resort to numerics in other cases. We also numerically evaluated the non-optimized MID for non-Gaussian photon counting which was found mostly to be a loose upper bound on the actual amount of non-classical correlations contained in the state. However, there is a finite set of two-mode Gaussian states encompassing pure states for which the non-Gaussian MID is strictly lower than Gaussian AMID. In the next step, we investigated non-classical correlations for a special class of non-Gaussian continuous-variable (CV) Werner states [7]. Remarkably,

for a one-parametric subclass of the states comprised by mixtures of two-mode squeezed vacuum with vacuum both discord and AMID can be computed analytically and they coincide. Besides, Gaussian discord for such states is strictly larger than discord (see Fig. 1) which is achieved by photon counting.

Non-classical correlations of the state thus can be extracted optimally only by means of the non-Gaussian measurement with infinite number of components and

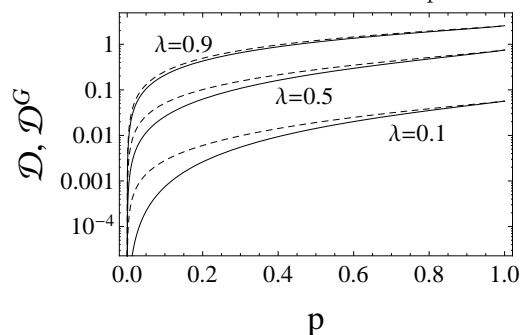


FIG. 1: Logarithmic plot of quantum discord  $\mathcal{D}$  (solid curve) and Gaussian quantum discord  $\mathcal{D}^G$  (dashed curve) versus the probability  $p$  of the two-mode squeezed vacuum state characterized by the parameter  $\lambda = \tanh r$  ( $r$  is the squeezing parameter) in the Werner state.

the state is thus a carrier of genuine CV non-Gaussian non-classical correlations. Our results thus demonstrate the necessity of non-Gaussian processing to correctly quantify non-classical correlations even in Gaussian states and pave the road toward this programme.

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