Annual Report 2005

Measurement and Information in Optics

Research Project of the Czech Ministry of Education
MSM 6198959213

This is the Annual Report 2005 of the Research Project of the Czech Ministry of Education MSM 6198959213 **Measurement and Information in Optics**. The Project is scheduled for the period of seven years 2005-2011 and its main objective is to provide proper framework for theoretical and experimental research in quantum optics, quantum information and modern wave optics. The Annual Report covers all the activities and results of contributing groups achieved within one year illustrating also the international collaboration. The aim of the Report is to inform broader scientific community about the current progress of our research and about topical problems of modern quantum and classical optics.

Olomouc, May 2006 Zdeněk Hradil

Optimal cloning and optimal partial measurement of quantum states

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Optimal quantum cloning

The linearity of quantum mechanics forbids perfect copying of unknown quantum states. Nevertheless, it is possible to make approximate clones of quantum states and this issue attracted a great deal of attention. Optimal quantum cloning machines for various sets of input states have been established and some of them were even demonstrated experimentally.

We have investigated several aspects of quantum cloning. First, we have determined the optimal universal asymmetric triplicator which produces three approximate copies of the state, each copy exhibiting different fidelity [1, 2]. This represents a novel class of highly asymmetric quantum cloners.

The implementation of the quantum cloning machine usually requires ancilla qubits which renders the experimental realization of these machines rather difficult. It is therefore interesting to know whether the cloning could be performed in a simplified "economical" manner without ancilla qubits. We have proved a series of no-go theorems for such cloners [3]. In particular, we proved the impossibility of constructing an economical version of the optimal universal $1 \to 2$ cloning machine in any dimension. We also showed that the d-dimensional $1 \to 2$ phase-covariant cloner, which optimally clones all uniform superpositions of computational basis states, can be realized economically only in dimension $d = 2$.

Optimal partial state estimation

Measurement of an observable of a quantum system inevitably disturbs the system. Moreover, the more information is gained about the observable the larger is the disturbance. Among all measurements the prime role is played by the so called minimum disturbance measurements (MDMs) which cause for a given information gain the least possible disturbance.

When seeking the MDMs for various sets of input states it is convenient to quantify the information gain by the mean fidelity G between the classical guess of the input state inferred from the measurement and the input state. Similarly, the measurement disturbance can be quantified by the mean fidelity F between the input state and the state at the output of the measurement.

In [4] we established a general method how to calculate optimal trade-off between the fidelities F and G for any continuous set of pure states of a d-level system which can be generated as an orbit of some group. Using this method we derived analytically the optimal trade-off for a single copy of an unknown pure state of a d-level system of the form $|\psi\rangle = \frac{1}{\sqrt{d}}\sum_{j=1}^{d} e^{i\phi_j}|j\rangle$. In Fig. 1 we have done the comparison of the optimal trade-off obtained by us with the optimal trade-off for a completely unknown single d-level system. We have also proposed schems for the implementation of these optimal partial measurements [5, 6].

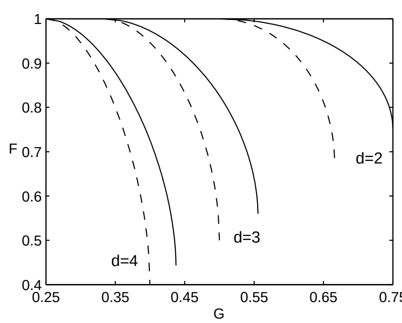

FIG. 1: Optimal trade-off between the fidelities F and G for a partially known state (solid curve) and a completely unknown state (dashed curve).

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[1] S. Iblisdir, A. Acin, N. J. Cerf, R. Filip, J. Fiurášek, and N. Gisin, Phys. Rev. A **72**, 042328 (2005).
[2] J. Fiurášek, R. Filip, and N.J. Cerf, Quant. Inform. Comp. **5**, 583 (2005).
[3] T. Durt, J. Fiurášek, and N. J. Cerf, and N. Gisin, Phys. Rev. A **72**, 052322 (2005).
[4] L. Mišta, Jr., J. Fiurášek, and R. Filip, Phys. Rev. A **72**, 012311 (2005).
[5] L. Mišta, Jr. and R. Filip, Phys. Rev. A **72**, 034307 (2005).
[6] L. Mišta, Jr. and R. Filip, Phys. Rev. A **71**, 022319 (2005).

Exploiting single-photon subtraction for quantum state engineering and quantum information processing

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Single-photon subtraction has recently emerged as a new major tool for manipulating the quantum states of light. Stimulated by the successful experimental demonstration of the single-photon subtraction from a pulsed squeezed vacuum state [1] we have investigated two possible applications of this technique.

The single photon subtraction allows to prepare a non-Gaussian entangled state from a two-mode squeezed vacuum. We have shown that this state could be used to demonstrate the violation of Bell inequalities with balanced homodyning [2], which is impossible to accomplish with Gaussian entangled states. The major advantage of this approach is that it allows to simultaneously close both the detection and locality loopholes, which up to date plagued all the experimental tests of Bell inequality violation. The proposed setup is shown in Fig. 1.

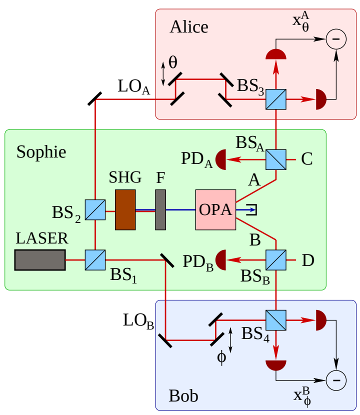

FIG. 1: Testing Bell inequality violation with balanced homodyning. The laser beam is converted into second harmonic in a nonlinear crystal (SHG). The second harmonic beam pumps an optical parametric amplifier (OPA) which generates two-mode squeezed vacuum in modes A and B. Single photons are conditionally subtracted from modes A and B with the use of the beam splitters BS_A and BS_B and single-photon detectors PD_A and PD_B. Alice (Bob) measures a quadrature of mode A (B) using a balanced homodyne detector that consists of a balanced beam splitter BS_3 (BS_4) and a pair of highly-efficient photodiodes.

As a second application we have shown that an arbitrary single-mode quantum state of light can be engineered from single-mode squeezed vacuum via a sequence of conditional single-photon subtractions and coherent displacements [3], see Fig. 2. More precisely, with N subtractions we can generate any state of the form $\sum_{n=0}^{N} c_n|n\rangle$, where $|n\rangle$ denotes the Fock state.

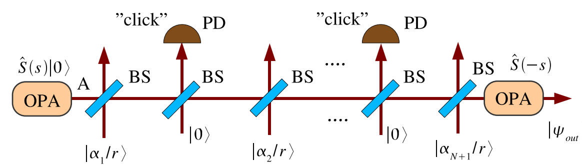

FIG. 2: Generation of arbitrary single-mode states of light. An optical parametric amplifier (OPA) generates a single-mode squeezed vacuum state which then propagates through $2N+1$ highly unbalanced beam splitters BS, which realize a sequence of $N+1$ displacements interspersed with N conditional photon subtractions. A second squeezer is used to apply the final anti-squeezing operation. Successful state preparation is heralded by clicks of all N photodetectors PD. $|\alpha_j/r\rangle$ denote auxiliary coherent states required for the displacement operation.

In the forthcoming year we intend to further extend these investigations along several lines. In particular, it would be interesting to study which multimode states could be generated with the use of single-photon subtractions starting from multimode Gaussian states. It is also natural to ask whether multimode entangled non-Gaussian states prepared by this method could exhibit quantum nonlocality resembling e.g. the GHZ paradox.

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[1] J. Wenger, R. Tualle-Brouri, and Ph. Grangier, Phys. Rev. Lett. **92**, 153601 (2004).

[2] R. Garcia-Patron, J. Fiurášek, and N.J. Cerf, Phys. Rev. A **71**, 022105 (2005).

[3] J. Fiurášek, R. Garcia-Patron, and N.J. Cerf, Phys. Rev. A **72**, 033822 (2005).

Quantum memory for light

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Protocols for readout of the memory

Quantum memory for light forms a key ingredient of advanced quantum communication systems such as quantum repeaters. Recently, experimental storage of coherent states of light into atomic quantum memory has been reported [1]. In the storage protocol the light passes through the ensemble of Cesium atoms held in a glass cell at a room temperature and interacts off-resonantly with the atoms. After the passage the light beam is measured and an appropriate feedback is applied to the atoms.

We have investigated the methods how to read out the memory, i.e. to transfer the state of the atoms back onto light. For technical reasons, the storage protocol cannot be directly inverted and it is necessary to devise protocols that involve only a single passage of the read-out light beam through the ensemble and do not require subsequent measurement of the atoms and feedback on light.

Two kinds of protocols were suggested. The first procedure relies on a simultaneous passage of the read-out beam through the ensemble in two perpendicular directions [2]. In the second protocol two independent light beams are sent through the atoms in perpendicular directions and the output beams interfere on a balanced beam splitter [3], see Fig. 1. Both protocols achieve high readout fidelity beating the classical limits.

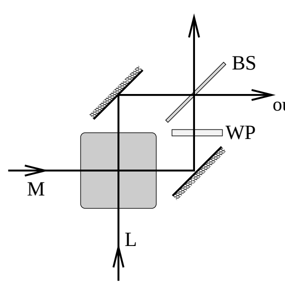

FIG. 1: Scheme for the single-passage read-out of the atomic quantum memory.

Enhancing the performance of quantum memory

In our work [4] we propose a method to increase the amount of quantum information stored and processed in an atomic sample. We exploit the structure of magnetic atomic levels and use additional Raman coupling lasers to store information about several optical modes into various atomic ground-state coherences. By properly choosing the frequency of the coupling laser in a scheme as in Fig. 2, we can design the interaction Hamiltonian in the form of beam-splitter coupling which is suitable for writing quantum information form the field to the medium and reading it back again. We can also obtain the two-mode squeezer type of coupling which would allow a direct preparation of the Einstein-Podolsky-Rosen entangled state between light and the atomic medium.

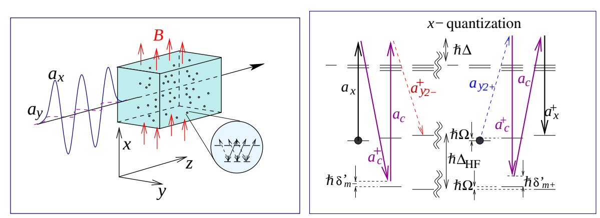

FIG. 2: Geometry of the setup and scheme of the interaction.

In the future work it would be interesting to explore the possibilities of applying higher Raman transitions and to study in more detail the quantum state evolution of the coupled system of light and atoms. Even though the beam-splitter like and the squeezer-like Hamiltonians are relatively simple, the long-pulse nature of the field and the small-size scale of the atomic sample can lead to rather complicated state-transfer properties.

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[1] B. Julsgaard, J. Sherson, J. I. Cirac, J. Fiurášek, and E. S. Polzik, Nature (London) **432**, 482 (2004).
[2] J. Sherson, A. S. Soerensen, J. Fiurasek, K. Moelmer, and E.S. Polzik, quant-ph/0505170; submitted to PRA.
[3] J. Fiurášek, J. Sherson, T. Opatrný, and E.S. Polzik, Phys. Rev. A **73**, 022331 (2006).
[4] T. Opatrný and J. Fiurášek, Phys. Rev. Lett. **95**, 053602 (2005).

Reduction of noise in continuous-variable quantum information processing

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Quantum communication and information processing with continuous variables (CVs), exploring quantum Gaussian states and operations, alternatively renders feasible protocols, that were previously based only only on discrete variables. An important task is to ensure a high fidelity transmission and manipulation of an unknown coherent state carrying information through a noisy channel. A straightforward method based on quantum repeaters is not possible in domain of purely Gaussian operations. An alternative way to faithfully transport a coherent state lies in analog error correction for the continuous variables, which is very challenging experimental task. We propose three methods how to get rid of the Gaussian noise in the processing in some particular important cases, only using the Gaussian operations.

First, the paper [1] presents an optimal quantum analogue of classical data averaging. In a classical data processing, if a Gaussian noise is superposed on N copies of the signal, measurement and data averaging can N-times reduce the variance of the excess noise. But an optimal measurement of non-orthogonal coherent states introduces a noise penalty. Fortunatelly, using quantum interference one can perform the averaging directly without any measurement. Based on this idea, an optimal quantum Gaussian purification of multi-copy noisy coherent states is experimentally investigated using only linear optics. By this method, an excess noise of quantum channel can optimally be also reduced N-times, see experimental results depicted on Fig.1. Recently, since a Gaussian noise in the signal can be unknown we are working on a feasible probabilistic non-Gaussian distillation of noisy coherent states.

Second, we propose a feasible method of mode decoupling in the multi-mode channel for quantum CV key distribution protocol with simultaneous measurements [2]. We prove that any passive mode coupling in the channel can be totally eliminated using only appropriate data manipulation obtained from the detections of both complementary quadratures of every channel mode. No interference between transmitted modes is required to implement the decoupling procedure. In future, we have a plan to experimentally investigate this method in a collaboration with Max-Planck group of G. Leuchs in Erlangen.

Third, we demonstrate that single-mode squeezers, phase-insensitive amplifiers as well as QND interactions can be accomplished with less noise by using only linear optical elements, homodyne measurements and off-line squeezed light beams [3]. In these schemes signal modes are coupled to ancillary modes in passive devices, the ancillary modes are subsequently detected and the measurement results are used to correct the optical signals using electro-optic modulator. Now, the measurement-induced operations are experimentally tested in a group of A. Furusawa in Tokio. In future, we would like to extend this concept to propose a measurement-induced high-order non-linear interaction based on single-photon detection.

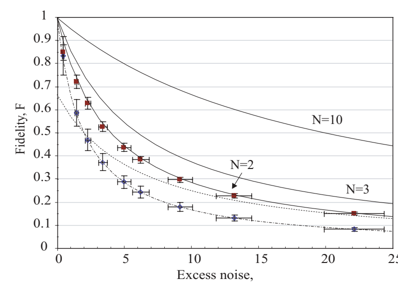

FIG. 1: Measured fidelity before (below) and after (above) purification of two noisy coherent states, as a function of an excess noise in the channel.

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[1] U.L. Andersen, R. Filip, J. Fiurasek, V. Josse and G. Leuchs, Phys. Rev. A **72**, 060301(R) (2005).
[2] R. Filip, L. Mišta, and P. Marek Phys. Rev. A 71, 012323 (2005).
[3] R. Filip, P. Marek, and U. L. Andersen Phys. Rev. A 71, 042308 (2005).

Quantum optics and multi-mode description of nonlinear processes

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We derive multi-mode generating functions, photon-number distributions, integrated-intensity distributions, moments and quadrature fluctuations for stimulated parametric down-conversion in relation to experiments measuring joint distributions. Parameters of the description can be determined from experimental data or from the evolution of dynamics of the process. The border between classical and quantum behavior is determined. These results represent a continuation of a similar investigation of the spontaneous process treated in J. Peřina and J. Křepelka: J. Opt. B: Quant. Semiclass. Opt. 7 (2005) 246. In future some effort will be given to remove some approximations necessary in this stage of the description.

We investigate the quantum statistics of trilinear time-dependent coupled oscillators in presence of the multi-photon processes. The system is connected with two atom multiphoton Tavis-Cummings model. The solution of the Heisenberg equations of the motion is obtained in a compact form. We assume that the modes are initially prepared in coherent states, and we discuss nonclassical phenomena (squeezing and sub-Poissonian behavior). Further we examine the joint quasidistribution functions as well as the photon-number distribution and its factorial moments. The system demonstrates that the nonclassical effect is apparent in compound modes. Moreover the superstructure phenomenon is observed when the photon transition is increased.

We study the effect of the Kerr-like medium on a system consisting of two level-atom and two fields injected simultaneously within perfect cavity. The present system can be regarded as a co-directional nonlinear coupler composed of two Kerr nonlinear waveguides, where the atom-field interaction plays the role of the energy exchange between the waveguides. The system includes two effective different coupling parameters such that each coupling connects the atom with one of the field mode. Moreover, it includes two different susceptibility factors, one represents self-coupling while the other is responsible for cross-action processes. Under certain condition the exact solution of the wave function in Schrödinger picture is obtained and Husimi quasidistribution is derived. A discussion of some physical phenomena, such as collapses and revivals, is given.

It is familiar that a well-behaved operator of the harmonic oscillator phase does not exist. Therefore, Turski's phase operator and Garrison's and Wong's operator may be at most defined in an interesting fashion and yield useful quantum expectation values. In this paper we touch a recent incomplete definition of a phase operator which has failed also in the respect that it can be completed only to a definition of an "incomplete" phase operator. We discuss, however, a possibility of completion of the definition and a relationship to the phase operator from an s-parametrized quasidistribution.

In the forthcoming research we will deal with the possibility of a compact formulation of the principles of the quantum theory of the electrodynamics in media respecting the optical polarization and the quantum fluctuations. We will determine quantum statistical properties of the light in periodic dielectric media, disordered media, and novel optical left-handed materials. We will define models of random lasers more exactly and in this framework we will determine statistics of optical modes. We will analyse experiments where the optics plays prominent role and either atoms or macroscopic detectors perform quasi-continuous or continuous measurements.

[1] V. Peřinová, A. Lukš, *Quantum phase from s-parametrized quasidistributions*, J. Opt. B: Quantum Semiclass. Opt. **7** (2005) S557–S562.

Spatial effects in mixed vortex states of light

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Though the concept of a phase of wavefield is rather abstract, and the idea of its singularity perhaps more so, the peculiar properties associated with phase dislocations of light have excited research activities resulting in realistic and very promising results. In recent years, a particular attention has been focused on the so-called optical vortices possessing helical wavefronts with spiral phase singularities. The vortices nested in well localized laser beams can exhibit interesting spatial effects manifested as looped, knotted, linked or braided vortices, rotation of vortex structures, attraction or repulsion of vortex pairs, annihilation and nucleation of vortices, colored vortices, dynamical nonlinear interactions of vortices or singularity induced Doppler effect. Very attractive are also quantum properties of vortices and in particular dynamical aspects of vortices associated with their angular momentum. A systematic research of light vortices seems to be prospective for applications in metrology, nonlinear optics, photolitography and information processing. The optical vortices have also been utilized for electron acceleration and for guiding, manipulation and sorting of electrically neutral particles and atoms. Except of optical applications, a multidisciplinary character of the research of vortex structures is also important. The developed methods can be used for investigation of phase dislocations in waves of different nature. For example, very perspective areas are quantum physics, where the vortices can be adopted as higher-dimensional states of the orbital angular momentum and matter physics where the vortices are realized in Bose-Einstein condensates.

Recently, a connection of principles of vortex and nondiffracting optics has been proposed and examined theoretically and experimentally [1, 2]. It enables realization of propagation invariant vortex beams and variable vortex patterns resistent against amplitude and phase perturbations. In paper [3], the spatial degrees of freedom of the nondiffracting vortices have been utilized for encoding, transfer and decoding of information applicable to the free-space communications. In the proposed method, the information is carried by a spatial structure of a mixed vortex field so that additional bits of information can be encoded into each pulse. By this way, the information density can be significantly increased. In the original set-up, a dynamical creation of the vortex superposition carrying an actual information code has been realized by the spatial light modulator with a limited repetition rate. In paper [4], the optical set-up enabling generation of variable vortex superpositions by a single static hologram has been proposed and examined. In this case, an actual information code has been created by a standard dynamical modulation of an array of spatially separated point sources illuminating the static optical system. In paper [5], a principle enabling controllable excitation of fiber modes has been proposed and experimentally verified. We have demonstrated a dynamical switching, phase coupling and weighted mixing of fibre modes achieved by a spatial modulation of the beam focused to the fibre. This experiment is promising for application of the vortex information encoding to fiber communications.

In the forthcoming research, our activity will be focused on theoretical and experimental problems of information transfer enabled by mixed vortex fields. In a detailed study of the proposed principle, an influence of the factors limiting the information density will be examined. A special attention will be devoted to the information decoding strongly influencing cross-talks of the information channel. Separately, the mechanical effects of the vortex fields will be included in our research. The "interference" law providing total orbital angular momentum of the multi-mode vortex field will be examined. An influence of the spatial distribution of the orbital angular momentum on behavior of trapped particles will also be studied.

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[1] Z. Bouchal: Physical principle of experiments with pseudo-nondiffracting fields, Czech. J. Phys. **55**, 1223-1236 (2005).
[2] Z. Bouchal: Spatially localized vortex structures, Progress in Electromagnetcic research, Ed. J.A. Kong, EMW Publishing, Cambridge (30 pages, in print).
[3] Z. Bouchal, R. Čelechovský: Mixed vortex states of light as information carriers, New J. Phys. **6**, 131-145 (2004).
[4] R. Čelechovský, Z. Bouchal: Generation of variable mixed vortex fields by a single static hologram, J. Mod. Opt. **4**, 473-480 (2006).
[5] Z. Bouchal, O. Haderka, R. Čelechovský: Selective excitation of vortex fibre modes using a spatial light modulator, New J. Phys. **7**, 125-139 (2005).

Information processing with vortex beams

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Light is a very convenient medium for the exchange and processing of information. Using light, one can encode information with a very high density, transmit information with the maximum possible speed, process information using optical methods, and, finally, decode the received information by means of a suitable photodetection. The encoding and decoding processes are the basic operations realized in communication systems.

A conventional communication chain consists of a light source, a source encoder, a transmitter, a communication channel and a receiver with a source decoder. The available communication systems enable one to modulate the light source at a rate approaching tens of gigahertz so that the information stored on hundreds of floppy disks can be transmitted in one second. Nevertheless, the information revolution requires further progress resulting in ultra-high data density, in new encoding and decoding schemes and techniques providing high security of the transferred information. One of the promising ways how to increase the information density is the application of the special types of laser beams called *optical vortices*, enabling the encoding of information into their spatial structures.

Spatial distribution of the light fields associated with the phase singularities may be adopted for the information encoding and processing. New emerging techniques based on the application of light vortices will be studied theoretically and experimentally. The goal is to use the controllable superposition of the vortex modes with different angular momenta as a basis for encoding of several bits of information into the spatial structure of a single pulse. The dynamical control of vortex superpositions has been realized by means of the spatial light modulator operating as the intensity modulating element. The basic principle of the method has already been verified and realized experimentally.

In paper [1] we have proposed and realized a novel decoding scheme motivated by quantum state estimation technique capable of extracting full information encoded into an array of Bessel-Gauss beams. Due to its nondiffracting character, the mixed vortex field then propagates as a structurally stable beam to a receiver. The topological charges of the vortices are "markers" enabling their spatial separation and the decoding of information. This is usually done applying intensity detection on the signal transformed by a suitable complex phase mask. Such a hardware decoding the analysis can be done adopting a proper reconstruction analysis (i.e. software) of detected images at the receiving station. This analysis was capable to extract full information encoded into weights of a superposition of Bessel-Gaussian beams. Simple communication based on transmitting up to four vortices simultaneously was verified experimentally.

In paper [2] we have investigated the uncertainty relation for angle and angular momentum. To avoid the problems linked to the periodicity, we proposed to quantify the second-order moments by the dispersion and used the exponential of the angle instead of the angle itself. We found states that minimize the uncertainty product under the constraint of a given uncertainty in angle or angular momentum. It turned out that these minimum states were not Gaussian, but were given by Mathieu wavefunctions.

In the forthcoming research we want to apply quantum theory to information processing with light beams. We are searching for ultimate limitation of information obtained by means of a measurement (decoding) in the form of uncertainty relations. The goal is to find the ultimate restrictions imposed on the measurements of the transversal spatial distribution of light. Quantum signals saturating such uncertainty relations can be regarded as optimal information carriers in singular optics. Furthermore, such theory can be applied to the reconstruction of the orbital momentum states of a photon.

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[1] J. Řeháček, Z. Hradil, Z. Bouchal, and M. Ježek: Tomographic analysis of vortex information content, J. Mod. Opt. 53, (Special Issue on Quantum Imaging) 689-697, 2006.

[2] Z. Hradil, J. Řeháček, Z. Bouchal, R. Čelechovský, L. L. Sánchez-Soto: Minimum uncertainty states for angle and angular momentum, in preparation.

Maximum Likelihood tomography

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The development of effective and robust methods of quantum state reconstruction is a task of crucial importance for quantum optics and information. Such methods are needed for quantum diagnostics: for the verification of quantum state preparation, for the analysis of quantum dynamics and decoherence, and for the information retrieval.

All the current successful applications of tomography schemes rely on three key ingredients: on a particular tomographically complete measurement available, on a suitable representation of quantum states, and on an adequate mathematical algorithm used for inverting the measured data. In addition, the entire reconstruction scheme must be robust with respect to noise. In real experiments the presence of noise is unavoidable due to losses and due to the fact that detectors are not ideal. The presence of losses poses a limit on the accuracy of a reconstruction. However, the very presence of losses can be turned into advantage and used for the reconstruction purposes.

In the paper [1] we have proposed the reconstruction procedure optimized with respect to the experimental set-up, representation and inversion. The scheme is called biased tomography and we have reported on an intrinsic relationship between the maximum-likelihood quantum-state estimation and the representation of the signal. Quantum analogy of transfer function determines the space where the reconstruction should be done without the need for any *ad hoc* truncations of the Hilbert space. The illustration of this method is provided by a simple yet practically important tomography of an optical signal registered by realistic binary (on/off) detectors.

In the paper [2] inspired by the neutron optics we have proposed and numerically analyzed an experiment in order to determine the quantum state of the center of mass motion of neutrons. Interference induced by momentum kicks and phase shifts are analyzed showing the possible non-gaussian behavior of the superposed wave packet of neutrons. The survey of tomographic methods used in neutron optics has been addressed in the review [3].

The research on tomographic methods addressed several other issues related to quantum tomography. We have clarified [4] the relationship between the choice of likelihood and statistics of registered data. Approximative solution of maximum likelihood extremal equations has been proposed in [5]. Here the solution of standard reconstruction may be corrected by means of linear perturbation technique.

In the future research we want to focus several issues. We would like to more develop the biased tomography scheme, apply it to homodyne detection and consider the performance measures such as e fidelities. In absorption tomography we would like to work out the maximum likelihood assisted by maximum entropy estimation. In optics we would like to consider the tomographic techniques for analysis of vortex beams.

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[1] Z. Hradil, D. Mogilevtsev, J. Řeháček, Biased tomography schemes: an objective approach, submitted to Phys. Rev. Lett. 2005

[2] G. Badurek, P. Facchi, Y. Hasegawa, Z. Hradil, S. Pascazio, H. Rauch, J. Řeháček, T. Yoneda, Neutron wave packet tomography, submitted to Phys. Rev. A 2005

[3] J. Řeháček et al., Advanced Neutron Imaging and Sensing, submitted to Advances in imaging and electron physics, 2005

[4] Z. Hradil, J. Řeháček, Comment on "Experimental reconstruction of photon statistics without photon counting", submitted to Phys. Rev. Lett. 2005

[5] P. Banáš, J. Řeháček, Z. Hradil, Perturbative quantum state estimation, submitted 2006

Photon-counting detectors and spatial correlations in down-conversion

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Following previous work on the development of a detector with partial photon-number resolution in the form of a fiber-delay-loop that has been successfully used for detection of photon-number statistics of various quantum states, two new approaches have been employed for similar goals.

First, a different version of a detector using fiber-delay lines has been constructed and its properties characterized [1], mimicking an approach used by another group. This detector is currently under reconstruction with a hope for certain improvement and is planned to be used in a forthcoming experiment.

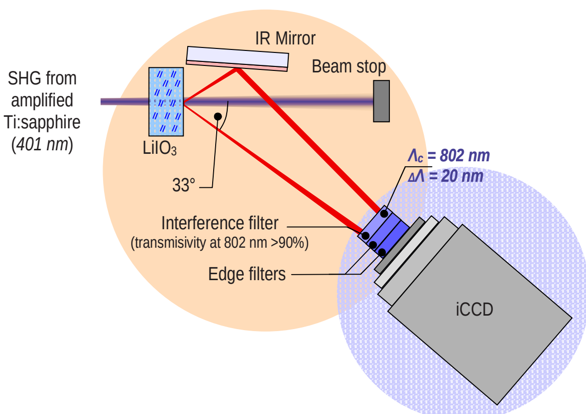

FIG. 1: Scheme of the experimental setup.

Major effort has been devoted, however, to the development of photon-counting techniques using the intensified CCD camera (iCCD). The iCCD represents a massively multichannel matrix of single-photon-sensitive detectors that can be used to detect quantum fields with higher mean photon-number than the fiber-loop detectors. A nontrivial approach for image data processing has been suggested and used for measurement of quantum-correlated fields obtained by parametric down-conversion process.

Violation of a classicality criterion has been observed first on data reconstructed from measured signal-idler joint photon-number resolution using maximum-likelihood method [2] and—after some progress in net efficiency of detection—on the measured data directly. Also phase-space quasi-distributions obtained from measured data show nonclassical features.

Besides being an interesting tool for photon-number measurement, the intensified CCD camera exhibits a big potential for investigation of spatial correlations of light fields at a single-photon level.

Using a simple laboratory setup (see fig. 1), a method for direct measurement of the dimension of the area of correlation has been developed [3, 4]. The results obtained are not in full agreement with simplified theoretical models yet. The main reason lies probably in a complex spatial structure of the pumping beam (2nd harmonic of an amplified Ti:sapphire system) and its poor control in the present experiment.

In the next year main stress will be put on improvement and optimization of the data readout algorithms. Application of the iCCD for detection of fields obtained from various samples is scheduled. Also spatial properties of photon pairs generated in 1D photonic-band-gap structures [5, 6] made of GaN/AlN are planned to be studied.

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[1] M. Mičuda, Multichannel detector of photons, diploma thesis, Faculty of Science, Palacký University (2005).

[2] O. Haderka, J. Peřina, Jr., M. Hamar, J. Peřina, Direct measurement and reconstruction of nonclassical features of twin beams generated in spontaneous parametric down-conversion, Phys. Rev. A 71, 033815 (2005).

[3] O. Haderka, J. Peřina, Jr., M. Hamar, Simple direct measurement of nonclassical joint signal-idler photon-number statistics and correlation area of twin photon beams, J. Opt. B: Quantum Semiclass. Opt. 7, 2005, S572-S576.

[4] M. Hamar, J. Peřina, Jr., O. Haderka: Intensified CCD camera - a new tool of research of photon pairs generated in spontaneous parametric downconversion, XV-th conference of Slovak and Czech physicists, Košice, Slovakia (2005).

[5] M. Centini, J. Peřina Jr., L. Sciscione, C. Sibilia, M. Scalora, M. J. Bloemer, M. Bertolotti, Entangled Photon Pair Generation by Spontaneous Parametric Down Conversion in Finite Length 1-D Photonic Crystals, Phys. Rev. A 72, 033806 (2005).

[6] J. Peřina Jr., M. Centini, C. Sibilia, M. Bertolotti, M. Scalora: Properties of entangled photon pairs generated in one-dimensional nonlinear photonic-band-gap structures, Phys. Rev. A, (2006) to appear.

Quantum information experiments

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We focus on optical implementations of simple procedures for manipulation of quantum states and quantum information processing. We use entangled photon pairs and interference of the fourth and second order.

Bulk Optics

In this subproject the experimental implementations are based on bulk optics. Qubits are encoded into polarization modes of light.

During the last year we tried to implement a phase-covariant cloning machine using a beamsplitter with adjustable splitting ratios both for vertical and horizontal polarizations based on the Mach-Zehnder interferometer. Linearity of quantum mechanics forbids exact copying of quantum states. However, approximate cloning is possible. We built an experimental setup for *symmetric phase-covariant cloning of qubits*. In our implementation qubits were encoded into polarization states of photons. The key component of our setup was a beamsplitter with adjustable splitting ratios both for vertical and horizontal polarizations. It was based on the Mach-Zehnder interferometer with two Soleil-Babinet compensators that served for the adjustment of proper phase differences for vertical and horizontal linear-polarization components independently. The ancilla and signal photons were generated by spontaneous parametric down conversion. Even if the function of the cloning device was qualitatively demonstrated there were so many problems with the adjustment and stability of the Mach-Zehnder interferometer that we were not able to obtain data with a reasonably small error. Therefore we have decided for another approach to implement a cloning device. Instead of the beamsplitter with adjustable splitting ratios we have used quantum-state filtering based on polarization dependent losses. Such filters can be conveniently realized by tilted glass plates. This new method, proposed by J. Fiurášek, enables to construct the universal, phase-covariant symmetric as well as phase-covariant asymmetric cloners. The experiment with the phase-covariant symmetric cloner (and the universal one for comparison) including the process tomography of the implemented operation is now in the run.

After finishing this experiment we intend to continue with the realization of a phase-covariant asymmetric cloner. And our next plan is to build a phase-covariant symmetric cloner using a different technique employing a custom-made beam splitter. Our aim is to compare different optical cloning techniques.

The idea of quantum-state filtering based on polarization dependent losses together with the Hong-Ou-Mandel-type interference is suitable also for realization of certain controlled unitary gates as recently proposed by J. Fiurášek. An interesting idea is to compare similar tasks implemented in bulk and in fiber optics. We also prepare the realization of a compact source of entangled photons pumped by semiconductor laser diode.

Fibre Optics

In this subproject the experimental implementations are based on fiber technology with an active stabilization of interference. Qubits and qutrits are encoded to spatial modes.

During the last half year we have experimentally realized the *encoding of two qubits to a single qutrit* [quant-ph/0603174]. We have found an optical scheme for the recently proposed protocol for encoding two qubits into one qutrit. In this protocol, Alice encodes arbitrary non-entangled states of two qubits into a state of one qutrit. Bob can then restore any of the two encoded qubit states but not both of them simultaneously. We have successfully realized this scheme experimentally using spatial mode encoding. Each qubit (qutrit) was represented by a single photon that could propagate through two (three) separate fibers. The experimental realization of the encoding transformation relies on the interplay of the fourth- and second-order interference. Further, we have proposed certain generalizations of the original protocol.

In the next period we intend to built a more complex device with two independent variable-ratio couplers. Such a device will be suitable either for cloning experiment, for realization of partial universal-not gate, or for implementation of linear optics two-qubit controlled unitary gates as recently proposed by J. Fiurášek. Besides, the theoretical proposal for yet another experiment is prepared by cooperating theorists (M. Gavenda and R. Filip). It concerns signal-recovery techniques behind a noisy channel. We also prepare the realization of a compact source of entangled photons pumped by semiconductor laser diode.

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The group of statistical and wave optics in 2005

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Gaining information about state and properties of object's surface is one of the most frequent measurements used in mechanics. Therefore there is putted such effort into research into optical methods. Optical method utilising correlation properties of speckle enables to obtain information about deformation state of elementary area of object's surface and slope of object's surface. To restore geometrical shape of object's surface spatial coherence profilometry can be used.

Research into speckle effect and its properties ran in two lines in 2005. In the first one the research was concentrated on modification of properties of a speckle pattern by means of a fractal object. Therefore different ways of generation of the fractal objects were investigated. Properties of intensity distribution of diffractals generated by regular and random Koch curves in the Fraunhofer plane were studied [1, 2].

In the second line there was studied practical utilisation of knowledge of statistical properties of speckle and its propagation in space in the area of mechanics. The research was concentrated on measurement of elastic deformation component ϵ_{xx} of small deformation tensor of object's surface by means of speckle correlation method [3–7].

Next a technique employing speckle pattern correlation method for detection of slope of object's surface was presented [8–10]. Controlled translation of an object under investigation and numerical correlation of speckle patterns recorded during its motion give information used for evaluation of tilt of the object. Proposed optical set-up enables to detect tilt of object's surface within the interval $(10 - 30)^\circ$.

The technique of speckle pattern correlation was also adapted for non-contact detection of stability of object's position [11].

Spatial coherence profilometry uses the Michelson interferometer with a monochromatic spatial extended light source. The object's surface under investigation represents a mirror of the interferometer. By moving of the measured object along the optical axis, the interefer-ence is observable only if the object's surface passes the so-called reference plane given by the position of the object mirror when the interferometer is balanced. A CCD camera is used as a detector. This method does not require a broadband light source contrary to white-light interferometry. [13, 14].

Next research should be concentrated on study of propagation of diffractal in free space, properties of fractal speckle, utilisation of speckle correlation method in measurement of object velocity and development of spatial coherence profilometry.

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[1] P. Neumannová, P. Horváth, P. Šmíd, M. Hrabovský, *Chinese Journal of Physics* (Under Review).

[2] P. Neumannová, P. Horváth, P. Šmíd, M. Hrabovský, *Fine Mech. Opt.*, 2005, **50** (10), pp. 294–299.

[3] P. Horváth, P. Šmíd, M. Hrabovský, P. Neumannová, *Experimental Mechanics* (Under Review).

[4] P. Horváth, P. Šmíd, P. Wagnerová, M. Hrabovský, *Fine Mech. Opt.*, 2005, **50** (3), pp. 85–91.

[5] P. Wagnerová, P. Horváth, P. Šmíd, M. Hrabovský, in: *43rd International conference on Experimental Stress Analysis, June 7-9, 2005, Skalský Dvůr, Czech Republic*, Proceedings of Extended abstracts, 2005, pp. 109–110.

[6] P. Wagnerová, P. Horváth, P. Šmíd, M. Hrabovský, in: *43rd International conference on Experimental Stress Analysis, June 7-9, 2005, Skalský Dvůr, Czech Republic*, Electronic Version of Proceedings, 2005.

[7] P. Horváth, P. Šmíd, P. Wagnerová, M. Hrabovský, in *22nd Danubia-Adria Symposium on Experimental Methods in Solid Mechanics, September 28 - October 1, 2005, Monticelli Terme - Parma, Italy*, Proceedings of Extended abstracts, 2005, pp. 46–47.

[8] P. Šmíd, P. Horváth, P. Neumannová, M. Hrabovský, *Applied Optics* (Under Review).

[9] P. Šmíd, P. Horváth, P. Wagnerová, M. Hrabovský, in *SPIE International Symposium Optical Metrology 2005 - Optical Measurement Systems for Industrial Inspection IV, June 13-17, 2005, Munich, Germany*, W. Osten, Ch. Gorecki, E. Novak, eds., *Proc. SPIE* **5856**, 2005, pp. 640–645.

[10] P. Horváth, P. Šmíd, P. Wagnerová, M. Hrabovský, in *ICO20: Optical Design and Fabrication, August 21-26, 2005, Changchun, China*, *Proc. SPIE* **6034**, 2005, pp. 511–516.

[11] M. Hrabovský, P. Horváth, P. Šmíd, Patent (registration number: 295817), registered at Industrial Property Office (Czech Patent and Trademark Office in Prague).

[12] P. Šmíd, H. Hiklová, *Fine Mech. Opt.*, 2005, **50** (1), pp. 17–19.

[13] P. Pavlíček, Z. Duan, M. Takeda, in *DGaO Proceedings 2005* - http://www.dgaoproceedings.de - ISSN: 1614-8436.

[14] P. Pavlíček, in *Proceedings of the 15th Conference of Slovak and Czech Physicists, Kosice, September 5-8 2005*, to be published.