Annual Report 2006

Measurement and Information in Optics

MSM 6198959213

and

Center of Modern Optics

LC06007

This is the Annual Report 2006 of the projects supported by the Czech Ministry of Education MSM 6198959213 **Measurement and Information in Optics** and LC06007 **Center of Modern Optics**. The Report covers all the activities carried on the Department of Optics, Palacky University within one year period. The Report is written on "one-page basis" where each activity and results achieved should be described on a single page of standard format. We believe that this is the most effective way how to inform the scientific community about our current problems, international collaboration and progress of our research in the fields of modern optics and quantum information.

Olomouc, January 2006

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coordinator of the project MSM6198959213

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Quantum information experiments based on fiber optics

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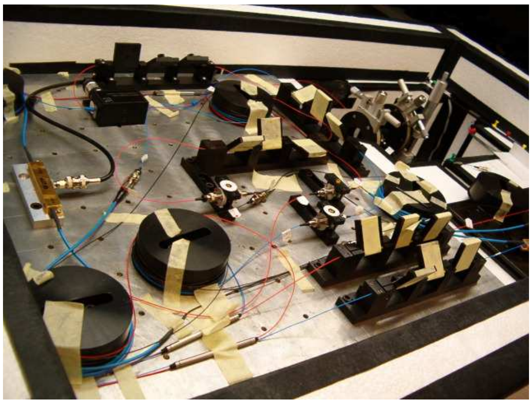

FIG. 1: Part of the experimental setup with the shielded Mach-Zehnder interferometer.

Our laboratory is focused on various aspects of quantum information processing. In most experiments, time-energy entangled photon pairs obtained from type-I parametric fluorescence in nonlinear crystals are used. Their polarization states, space-time properties and other features are manipulated and then the photons undergo various combinations of second- and fourth-order interference schemes. The results obtained from detection systems, ranging from simple two-detector coincidence to incomplete Bell-state analysis, are interpreted in quantum information terms.

In this subproject the experimental implementations are based on fiber optics. Qubits (qutrits) are encoded to spatial modes, e.i. single photons propagate through two (three) distinct fibers. We have experimentally realized an optical scheme for encoding of two quantum bits into one qutrit. From this qutrit, either of the original qubits can be error-free restored, but not both of them simultaneously [1, 2, 4, 5].

Figure 1 shows the essential part of the setup, a fiber based Mach-Zehnder interferometer. Due to the fact, that the interferometer is highly sensitive to thermal fluctuations, it is situated in a shielding box. Moreover, the interferometer has to be actively stabilized during the measurement.

During the last half year we rebuilded the setup to ensure experimental implementation of the optimal $1 \rightarrow 2$ phase-covariant cloning of photonic qubits, see Fig. 2. The cloning operation is realized by the interference of the input photon with an ancilla photon on a variable-ratio couplers. The main advantage of this implementation is based on the fact, that the splitting ratio of the couplers can be easily changed. This condition enables us to set the asymmetry of the fidelities of the two clones. In the experiment, we demonstrated the optimal symmetric cloning with fidelities: $F_A = (85.4 \pm 0.4)\%$, $F_B = (83.4 \pm 0.4)\%$. Then we enhanced the asymmetry. With this scheme we were able to exceed the limit of universal cloning machine [3].

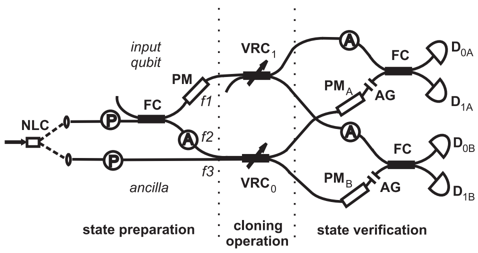

FIG. 2: Scheme of the asymmetric-cloning setup.

This research was supported by the projects of the Ministry of Education of the Czech Republic (MSM 6198959213, LC06007 and 1M06002) and by the SECOQC project of the EC (IST-2002-506813).

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[1] L. Bartůšková, A. Černoch, R. Filip, J. Fiurášek, J. Soubusta, M. Dušek, Optical implementation of the encoding of two qubits to a single qutrit, **Phys. Rev. A 74**, 022325 (2006).

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Quantum information experiments based on bulk optics

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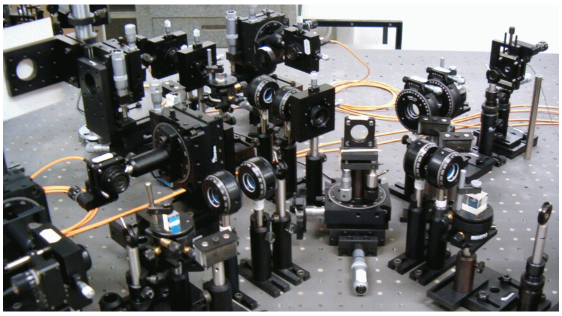

FIG. 1: Essential part of the experimental setup with the custom-made beamsplitter in the center.

Our laboratory is focused on various aspects of quantum information processing. In most experiments, time-energy entangled photon pairs obtained from type-I parametric fluorescence in nonlinear crystals are used. Their polarization states, space-time properties and other features are manipulated and then the photons undergo various combinations of second- and fourth-order interference schemes. The results obtained from detection systems, ranging from simple two-detector coincidence to incomplete Bell-state analysis, are interpreted in quantum information terms.

In this subproject the experimental implementations are based on bulk optics. Qubits are encoded into polarization states of individual photons. During the last year we built and tested several setups, that can be used for cloning of polarization qubits. Linearity of quantum mechanics forbids exact copying of unknown quantum states. However, approximate cloning is possible.

Figure 1 shows one scheme, where the key element is a special beamsplitter with splitting ratio different for horizontal polarization (21:79) and vertical polarization (79:21) [1–3]. Because the splitting ratio of the custom-made beamsplitter manufactured by Ekspla is not perfect, we balanced it by a glass plate (GP), shown in fig. 2. This quantum-state filtering is based on polarization dependent losses. The fidelities of both clones measured with the GP coincide within the measurement error, $F_1 = F_2 = 82.2 \pm 0.2\%$. From the measured data we estimated the implemented cloning transformation using the maximum-likelihood method. The result shows that this realized transformation is very close to the ideal one and the map fidelity reaches 94%.

In the next period our aim is to thoroughly compare different cloning techniques. These experiments are actually in the run. This research is interesting not only from the theoretical point of view, but it demonstrates different cloning technologies and strategies of compensation of unperfect optical components.

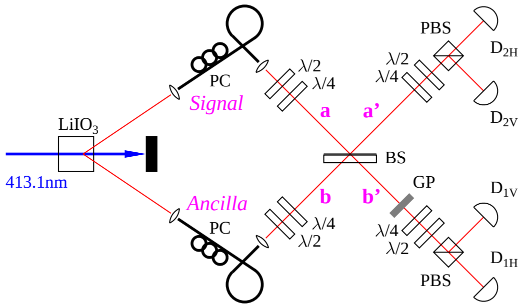

FIG. 2: Scheme of the cloning setup.

This research was supported by the projects of the Ministry of Education of the Czech Republic (MSM 6198959213, LC06007 and 1M06002) and by the SECOQC project of the EC (IST-2002-506813).

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Photon-counting detectors, spatial correlations in down-conversion and new sources of entangled photon-pairs

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We have continued our research towards construction and application of two types of photon-counting detectors — fiber-loop detectors and iCCD cameras. An experiment devoted to the measurement of a pairwise character of photon-number distribution generated in the process of second-subharmonic generation and using a fiber-loop detector is in preparation. Motivated by one of our previous experiments, a source of photons with selectable super-poissonian statistics is being developed. It is based on a well characterized laser diode, the pumping current of which undergoes random fluctuations with prescribed statistics. Its experimental characterization will be done using a fiber-loop detector. On the other hand, an iCCD camera [1] has been extensively used in the measurement of the dependencies of the size of area of correlation on the geometry of the pumping beam [2, 3]. Correlation areas both in the near field (position correlation) and far field (momentum correlation) have been determined both for femtosecond and cw pumping. Agreement of the experimental data with approximate theories is not perfect at present but a great improvement has been done compared to the initial results [2]. This improvement has been reached also due to new and improved algorithms for the readout of the data from the iCCD camera [4]. A new generation of the data processing software is currently in the development.

We have made an extensive test of a new type of single-photon cameras - electron-multiplying cameras (EMCCD) - in our typical laboratory setups and concluded that EMCCDs show spurious charge noise [5] that is too high for our needs.

As one of the perspective sources of entangled photon pairs nonlinear layered structure made of GaN/AlN have been considered both theoretically and experimentally. A quantum vectorial model of spontaneous parametric down-conversion [6–8] has been developed to study properties of the generated photon pairs and suggest suitable structures [9]. We have reached progress in the development of the detection methods for detecting low signals, however no provable detection of the down-converted field has been achieved yet, mainly due to large luminous noise coming from the substrate of the samples. Also a nonlinear waveguide with perpendicular pumping made of LiNbO3 has been studied [10]. This configuration is highly tunable in the parameters characterizing the emitted photon pairs.

Two members of the group, O. Haderka and J. Peřina Jr., were awarded by Otto Wichterle prize of Academy of Sciences of the Czech Republic.

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Linear-optics Quantum Toffoli and Fredkin gates

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One of the long-standing goals of quantum information science is the construction of a quantum computer, which is a device that could apply arbitrary desired unitary transformation to the quantum register consisting of quantum bits. Quantum computer would allow to efficiently simulate evolution of quantum systems and to efficiently solve certain purely classical problems such as factoring of integers.

During recent years, many architectures for the quantum computer have been proposed, ranging from trapped ions to nuclear magnetic resonance systems. In 2001, Knill, Laflamme and Milburn shown that it is, in principle, possible to construct an all-optical quantum computer, which requires only single-photon sources, passive linear optics and single photon detectors. In this approach, the interaction between single photons is simulated by using ancilla single photons, measurement and feedforward. Several schemes for implementation of the fundamental two-qubit controlled-NOT gate have been proposed and demonstrated experimentally.

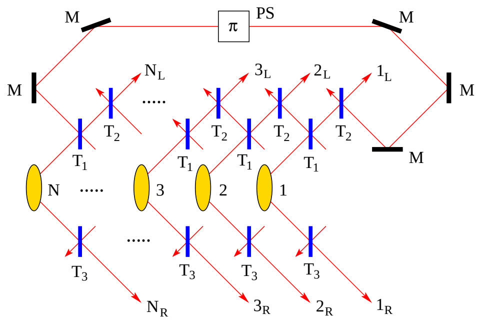

FIG. 1: Scheme for N-qubit Toffoli gate in coincidence basis.

Arbitrary multiqubit quantum gate can be decomposed into a sequence of single-qubit gates and CNOTs. However, the current optical CNOT gates work only probabilistically and it is difficult to concatenate several of them because this would require too many ancilla photons. This suggest that it might be useful to seek other implementations of the multiqubit quantum gates. Of particular importance are the fundamental Toffoli and Fredkin gates, which find applications e.g. in quantum error correction. We have devised schemes for direct optical implementation of these gates, which achieve much higher probability of success and require less ancilla photons than implementations relying on a sequence of single- and two-qubit gates [1].

The proposed scheme for the all-optical generalized N-qubit Toffoli gate is shown in Fig. 1. The operation of this gate is based on the multiphoton interference of the photons on an array of beam splitters. The gate works in the so-called coincidence basis, i.e. it succeeds if a single photon is observed in each pair of output modes j_L, j_R. The advantage of this approach is that no ancilla photons are needed so for $N = 3$ or $N = 4$ this gate could be demonstrated with present technology.

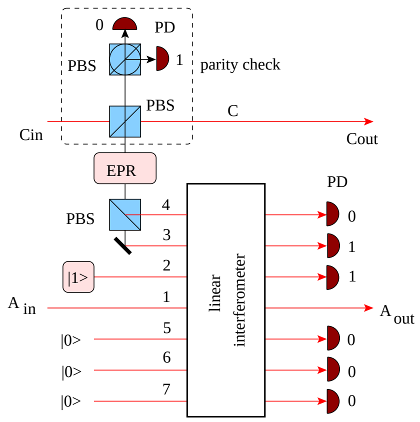

FIG. 2: Simulation of cross Kerr interaction between two modes.

The Fredkin gate – a controlled SWAP – can be realized using a Mach-Zehnder interferometer with phase shift in one of its arm controlled by the state of the control qubit via a nonlinear cross Kerr effect. The optical scheme which simulates the cross-Kerr interaction in the relevant subspace of the total Hilbert space of the two modes A_{in} and C_{in} is shown in Fig. 2. The scheme requires an auxiliary maximally entangled photon pair as well as an additional ancilla single photon. The design of the linear interferometer is described in detail in Ref. [1] and the scheme is successful if the detectors register the indicated pattern of single photons and vacuum states.

In the future we plan to design schemes for other interesting two-a and multi-qubit quantum gates and possibly attempt their experimental demonstration.

This work was supported by the the Czech Ministry of Education under projects "Measurement and Information in Optics" MSM 6198959213 and "Centre of Modern Optics" LC06007.

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Experimental distillation and purification of non-Gaussian squeezed states

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Entanglement of Gaussian states cannot be distilled by means of local Gaussian operations. Similarly, it can be proved that squeezing of a Gaussian state state cannot be enhanced by passive linear optics, homodyning and feedforward, even if several copies of the state are available. These no-go theorems put a strong limit on our ability to distribute entanglement or squeezing required for quantum communication with continuous variables. However, if the noise which degrades the squeezing is non-Gaussian, then the above theorems do not apply any longer and it becomes possible to distill the squeezing and/or entanglement of such states solely by Gaussian operations. Distillation of single-mode squeezing has been demonstrated experimentally in collaboration with the groups of G. Leuchs in Erlangen and R. Schnabel in Hannover.

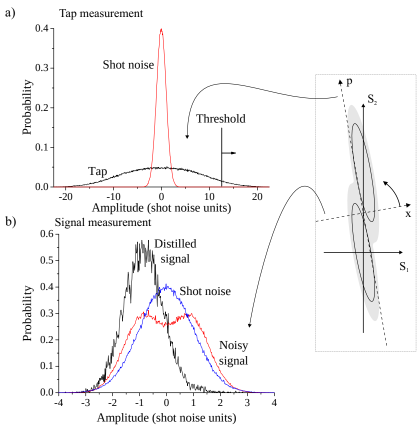

FIG. 1: Distillation of randomly displaced squeezed states.

In the first experiment, the noise was represented by a random displacement [1], which created a mixture of two squeeezed states from the input Gaussian state, see Fig. 1. The squeezing of a single copy of such state was probabilistically increased by tapping-off a part of the beam with an unbalanced beam splitter and performing homodyne detection on the tapped signal. The purification succeeded if the measured quadrature fell within certain interval, c.f. Fig. 1(a). In these cases the output purified beam was accepted and otherwise it was rejected. The net result of this procedure is the increase of the squeezing of the state, as witnessed by the difference between the quadrature distributions for input noisy signal and distilled signal, see Fig. 1(b).

The second experiment was designed to counteract the effect of random phase fluctuations, which are one of the dominant sources of noise in quantum communication over optical fibers [2]. Two copies of phase-diffused squeezed state interfere on a balanced beam splitter and the amplitude quadrature x_1 of one output beam is measured in a homodyne detector, see Fig. 2. The distillation succeeds if $|x_1|$ is less than some threshold. As demonstrated experimentally, the squeezing of the distilled copy exceeds the squeezing of the input noisy states. This protocol could be applied iteratively if more copies are available.

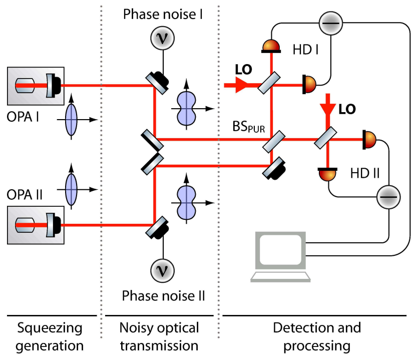

FIG. 2: Distillation of phase-diffused squeezed states.

In a related experiment, it was demonstrated that the purity of Gaussian squeezed states can be improved by tapping off a part of the beam, homodyne detection and feed-forward [3]. In this way the fluctuations of the anti-squeezed quadrature can be drastically reduced at the expense of only modest decrease of squeezing.

This work was supported by the the Czech Ministry of Education under projects "Measurement and Information in Optics" MSM 6198959213 and "Center of Modern Optics" LC06007 and EU project COVAQIAL FP6-511004.

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Minimal disturbance measurements

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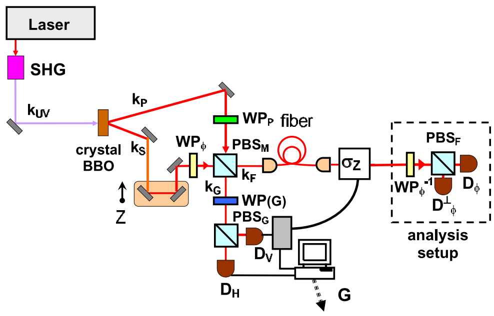

FIG. 1: Optical set-up implementing the MDM. The output qubit is characterized adopting the analysis setup illustrated in the dashed box.

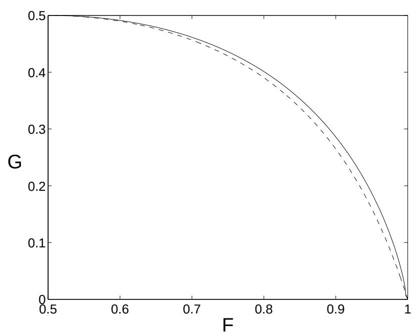

FIG. 2: Optimal Gaussian (dashed line) and non-Gaussian (solid line) fidelity trade-off.

There is not a quantum operation that would allow to extract some information on an unknown quantum state without disturbing it. Within the framework of the project we went on investigating the operations that introduce for a given information gain the least possible disturbance that are traditionally called minimal disturbance measurements (MDMs). For this purpose we used a convenient approach based on quantification of the information gain by the mean estimation fidelity G and the state disturbance by the mean output fidelity F [1]. For a MDM the two fidelities satisfy a specific trade-off relation that cannot be overcome by any quantum operation. In collaboration with the group of professor F. De Martini we proposed and experimentally demonstrated [2, 3] the MDM for a completely unknown and equatorial state of a 2-level particle (qubit) realized by a polarization state of a single photon (see Fig. 1).

Our studies did not restrict to finite-dimensional quantum systems and also optimal Gaussian MDM for a completely unknown coherent state of an optical field was found and experimentally demonstrated [4] in collaboration with the group of professor G. Leuchs. Both the experimental MDMs were reported in [5]. We further examined optimal fidelity trade-off for a completely unknown coherent state beyond the framework of Gaussian operations. We found that the aforementioned optimal Gaussian trade-off can be improved by up to 2.77% if we use a suitable non-Gaussian operation [6] (see Fig. 2). This operation can be implemented by the standard coherent state teleportation where the shared state is a suitable non-Gaussian entangled state. We also derived analytically optimal fidelity trade-off for N identical qubits and the corresponding MDM assuming quantum operations with a single output qubit [7].

The research has been supported by the research projects "Measurement and Information in Optics," (MSM 6198959213) and Center of Modern Optics (LC06007) of the Czech Ministry of Education and by the COVAQIAL (FP6-511004) and SECOQC (IST-2002-506813) projects of the sixth framework program of EU.

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Composed vortex fields and their orbital angular momentum

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In recent time, optical vortex structures have attracted increasing attention because they possess unique physical properties useful for applications. In the last year, we developed theoretical models and experimental methods providing results promissing for applications of optical vortices in wireless communications and MEMS (Micro Electro Mechanical Systems).

In [1], recent findings concerning nondiffracting beams, vortex beams and combinations of the two were reviewed. Particular attention was devoted to physical properties, experimental methods, and potential applications of single and composite vortex fields carried by a pseudo-nondiffracting background beam. Such beams may be dynamically controlled with a Spatial Light Modulator (SLM) for applications where beam reshaping, information encoding, or optical manipulation are required.

Considerable effort was also devoted to a development of the previously proposed method enabling encoding and transfer of information by means of mixed vortex fields. In this case, information is encoded into a spatial structure of optical field composed of several vortex beams with different topological charges. In a practical operation, information codes must be created sequentially. In experiments, it can be achieved adopting holographical methods realized by means of the SLM. Unfortunately, a relatively low repetition rate of available SLMs prevents utilization of this method in real communication systems. In [2], the holographical method was modified to enable an exploitable dynamical information encoding. In this case, various information codes can be created by the same single hologram. A required sequentiality of the information codes was ensured by a conventional switching of an array of point sources illuminating the single hologram. To transform incoming light into a coaxial superposition of vortices with well defined weight coefficients, the special phase only masks were designed and realized holographically. The phase masks were successfully tested in our laboratory. It was verified that they are applicable to both information encoding and decoding in a good agreement with theoretical predictions [3].

In the last year, the mechanical consequences of single and composed optical vortex fields were also examined. As is well known, the Orbital Angular Momentum (OAM) of a single vortex beam depends on its power and wavefront helicity. In [4], this relation was generalized for mixed vortex beams composed of several coaxial vortices with different topological charges. The obtained interference law indicated interference effects of the OAM resulting in local spatial gradients of the OAM density. Description of the OAM of mixed vortex beams was used for demonstration of a possibility to tune the OAM density of a composite vortex field without changing topological charges or intensity distribution. Experimental demonstration of the OAM tuning was discussed for interference of two focused vortex beams generated by means of a spiral phase mask. The specific distributions of the OAM density promising for trapping experiments were explored and demonstrated.

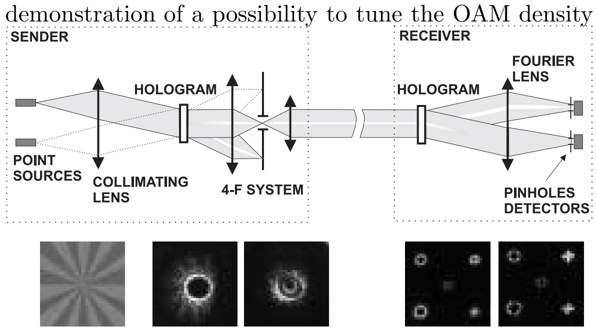

FIG. 1: Optical set up for transfer of information by means of composed vortex beams.

This work was supported by the Research Project of the Czech Ministry of Education "Measurement and Information in Optics" MSM 6198959213 and Grant 202/06/0307 of Czech Grant Agency.

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Tomographic methods for quantum information processing

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The investigation on tomographic methods and quantum estimation started recently was successful and resulted in several publications [1] last year. The current research has merged the fields of quantum information processing with vortex beams and advanced reconstruction techniques. The state of the art of this field is summarized in several items.

The publication [2] published at the end of the year has established the proper framework for quantum description of classical optics in terms of singular waves. This leads to novel formulation of uncertainty relations for orbital momentum and angle variable. Current problems discussed in the team are focussing on the improved detection of orbital momentum, on the issue of alternative resolution measures and full description of possible non-classical behavior. Special attention is payed to the novel concept of generalized measurements achieved by means of complex (amplitude and phase masks). The experimental capabilities has been enhanced by acquiring the Hartmann-Schak sensor, which is capable to analyze the wavefront of propagating wave.

The research on formal issues of Maximum-Likelihood algorithm has continued and resulted in submitted publication [3]. Here the generic form of numerical algorithm guaranteeing the convergence has been presented and detailed on several valuable examples. The concept of objective and biased tomography scheme was further detailed in accepted publication [4]. The intrinsic relationship between the maximum-likelihood quantum-state estimation and the representation of the signal was elaborated. A quantum analogy of the transfer function determines the space where a successful reconstruction can be achieved. This provides a tool for reducing the number of dimensions of the observed system based on physical characteristics of the reconstruction scheme rather than some *ad hoc* truncations. The method is illustrated with two examples of practical importance: an optical quantum homodyne tomography and a novel, simple, and robust tomography of an optical signal recorded by realistic binary detectors. The seminal scheme of homodyne detection from the viewpoint of objective tomography is detailed in [5]. The unpublished papers announced as Comment previous year will be further elaborated with Italian colleagues. The topic of standard tomography encountered certain progress recently [6]. Maximum likelihood assisted by maximum entropy is developed as a robust tool for analysis of noisy signals. Further research will focus on better numerical implementation of this algorithm.

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Quantum optics and statistics of nonlinear optical processes

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Multimode joint integrated intensity and photon-number probability distributions were derived for the stimulated process of optical parametric down-conversion in relation to measured experimental data and a border between classical and quantum behavior was determined [1, 2]. Quantum statistical properties for multi-photon three-boson coupled oscillators in the framework of the Tavis-Cummings model were obtained and the corresponding nonclassical properties of the system were deduced [3]. Such nonclassical behavior, including squeezing of vacuum fluctuations, sub-Poissonian behavior of photon statistics and collapse-revival phenomena were also investigated in a two-level atom influenced by Kerr-like medium [4] and for combined Kerr and down-conversion processes [5], which can be also interpreted in terms of nonlinear optical couplers.

A unified approach for estimating the cosine of phase and cosine of double phase in the Mach Zehnder interferometer has been proposed [6]. The phase sensitivity related to the Cramér-Rao lower bound of the estimator variance has been addressed. Fisher's measure of information has been compared with the usual measure of sensitivity of the SU(2), SU(1,1), and M(2) interferometers. The states of optimum Fisher information measure have been defined and their properties have been studied for the SU(2) interferometer [7]. Quantum-mechanical measurement of the z component of the angular momentum and the minimum uncertainty states with respect to the incompatible y and z components have been investigated [10].

The solutions of the time-independent Maxwell equations have been dealt with in the framework of Floquet theory for a particular choice of the dielectric function. A connection of the solutions (modal functions) with the results of the coupled mode theory has been investigated [8]. These results will be used to a "synthesis" of the quantum electromagnetic field in a dielectric medium. Quantum statistical properties of the light in periodic dielectric media, disordered media, and in the novel optical left-handed materials will be investigated as well.

The unitary evolution operator of a pure state of two modes of a quantized field has been factorized provided that the coupled modes of radiation are described with a quadratic Hamiltonian. A connection with the Baker–Campbell–Hausdorff formula has been explained [9].

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The group of statistical and wave optics in 2006

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Detection of components of small deformation tensor is an object of interest to industry and many research fields. The research of the group shows applicability of the speckle correlation method in measurement of elastic deformation, object's surface slope and object's velocity. The outputs of measurement of the elastic deformation component ϵ_{xx} proved equality of the results obtained by the optical method and direct contact method within the interval $(0 - 2100)\times 10^{-6}$ [1]. Research into detection of tilt of object's surface showed that the geometrical parameters of the designed experimental set-up limit the measuring range of the tilt [2, 3]. The proposed optical set-up enables one to detect tilt of object's surface within the interval $(10 - 30)^{\circ}$.

Gaining from knowledge of measurement of a translation component of the small deformation tensor a technique for measurement of in-plane velocity in one direction of diffusely reflective object is developed [4, 5]. Numerical correlations of speckle patterns recorded periodically by a linear CMOS detector during motion of the object under investigation give information used to evaluate object translations between each two consecutive records of the speckle patterns. The simulation analysis shows the way of controlling the measuring range and enables one to select a proper exposure time and acquisition rate. Proposed optical set-up similar to the one designed for measurement of object's surface slope uses a detection plane in the image field and enables one to detect the object's velocity within the interval $(10 - 150)\,\mu\mathrm{m}\cdot\mathrm{s}^{-1}$.

Next research into statistical properties of speckled speckle is under way. Comparison of statistical properties [6] (first-order statistics) of order and fractal speckle is presented. The subject of research is a diffractal generated by amplitude filters described by random Weierstrass functions.

White-ligth interferometry is an established method for measurement of the geometrical form of objects with optically smooth or rough surface. When the form of an object with optically rough surface is measured, speckle pattern arises in the image plane. The statistical nature of the speckle pattern gives rise to the measurement error of surface location. Numerical calculations show that measurement error caused by the surface roughness obeys Gaussian distribution [7]. The standard deviation of this distribution is the measurement uncertainty. The numerically calculated measurement uncertainty is compared with the measurement uncertainty that was derived analytically (but with strongly simplified conditions) in the previous work.

A spatial coherence analogy to white-light interferometry is spatial coherence profilometry [8]. It is interesting to compare the properties of both methods. A glass plate introduced into one arm of the white-light interferometer elongates the optical path. The influence of the glass plate on spatial coherence profilometry is opposite. In this case the arm with the glass plate seems to be shortened [9].

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