Annual Report 2007

Measurement and Information in Optics

MSM 6198959213

and

Center of Modern Optics

LC06007

The Annual Report 2007 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 - 2001** and LC06007 **Center of Modern Optics CMO 2006 - 2010**. Results of individual small teams described comprehensively on a single page are documenting the progress of our research in the fields of modern optics and quantum information processing. In the past year the project MIO was evaluated by the Evaluation Board of Ministry as top-ranking. Individual members of the team have achieved another remarkable achievement in the past year: Dr. Miroslav Ježek was awarded by the prestigious Votruba's price 2007 for his PhD thesis and Dr. Radim Filip was awarded by the Price of The Czech Grant Agency for his post-doc project.

Olomouc, January 2008

Zdeněk Hradil
coordinator of the project MSM6198959213

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Quantum information experiments based on fiber optics

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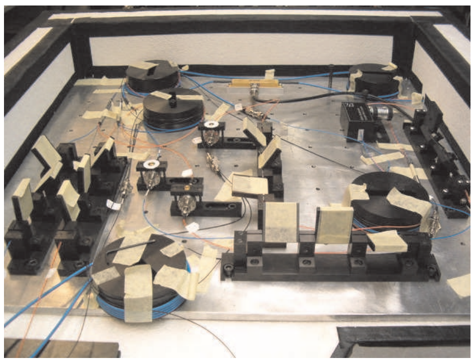

FIG. 1: Part of the experimental setup for phase-covariant quantum cloning thermally isolated in a polystyren box.

Our experiments are focused on optical implementations of various procedures from the field of quantum information processing. Depending on the character of each experiment we utilize an attenuated signal from a pulse laser as a source of coherent states or entangled photon pairs generated by type-I parametric process in a nonlinear crystal. In this subproject experimental realizations are based on optical fibers and fiber components.

In the first half of the year we finished measurements with the setup realizing optimal $1 \rightarrow 2$ phase-covariant cloning of photonic qubits. Qubit states are represented by single photons that can propagate through two different fibers. Copying of the state of signal qubit requires an ancilla qubit which is tightly time correlated with the signal qubit. Therefore photon pairs produced by down-conversion process in a nonlinear crystal are used for preparation of qubit states. We have realized symmetric and asymmetric phase-covariant cloning of qubit states lying on the equator of the Bloch sphere [1, 4]. Results measured for the symmetric cloning were compared with other implementations of quantum cloners realized in our laboratory [2, 5, 6].

During the last half year the setup was modified for measurement of unambiguous discrimination of weak coherent states. We have experimentally realized the basic implementation of discrimination protocol where an unknown coherent state can equal to two different states. The principle of operation lies in the interference of an unknown state with two program states. Implemented operation of state identification is probabilistic and the obtained values of probabilities of correct identification are in accordance with their theoretical predictions [3]. Experimental setup can be easily extended to higher numbers of program states and such a device can be used for quantum database search.

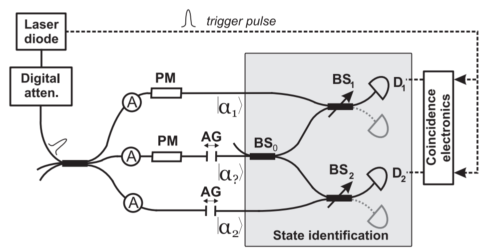

FIG. 2: Scheme of the setup for unambiguous discrimination of coherent states.

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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Quantum information experiments based on bulk optics

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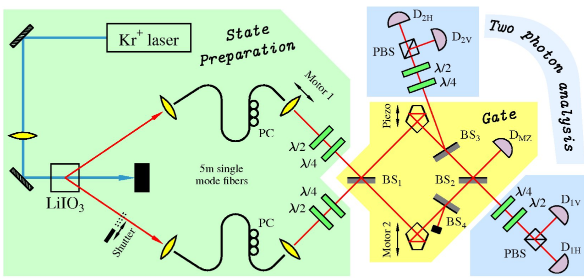

FIG. 1: Scheme of the partial-*SWAP* quantum gate.

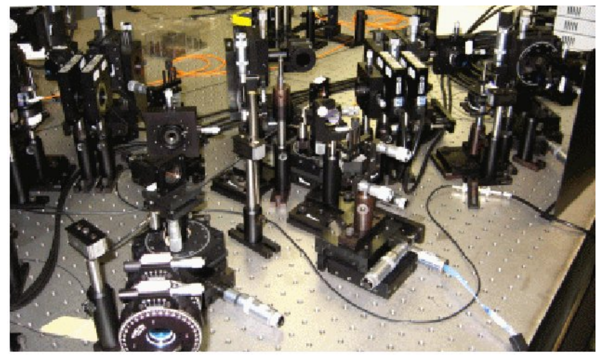

FIG. 2: Picture of the key part of the partial-*SWAP* quantum gate.

This part of laboratory of quantum information processing encode quantum information into the polarization states of single photons, that is why the bulk optics is used. Pairs of time-correlated photons are generated by type-I parametric down-conversion. Polarization states are set by means of wave plates, polarization analysis is made by wave plates and polarization beam-splitters.

In the spring we closed the field of the phase covariant cloning of an unknown quantum state. We ended up with the measurement of the symmetric and asymmetric quantum cloning machine based on a state filtration. The results of all schemes of symmetric cloning were summarized in Ref. [1]. Oral overview on this topic was presented as several conference contributions. Finally, last data measured with the asymmetric cloners will be presented in a paper which is in progress.

After that we started to build a new experiment on an empty table. Our work continued with the construction of the optical quantum gates. As the first subject we built a linear-optical implementation of a class of two-qubit partial-*SWAP* gates for polarization states of photons, see the scheme in Fig. 1. Different gate operations, including the *SWAP* and entangling $\sqrt{SWAP}$, can be obtained by changing a classical control parameter - namely the phase difference in the interferometer. Reconstruction of output states, full process tomography and evaluation of entanglement of formation proved very good performance of the gates [2].

Figure 2 shows the layout of the bulk components on the optical table. This scheme can be modified to ensure operation of the partial symmetrization gate, which we will be implementing next year.

This research was supported by the projects of the Ministry of Education of the Czech Republic (MSM 6198959213, LC06007 and 1M06002).

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[6] M. Dušek *et al.*, Various experimental realizations of symmetric and asymmetric phase-covariant quantum cloners, *Identifying quantum states and operations: theory and applications*, Budmerice, Slovakia, Jun 20-24, 2007.

Gaussian localizable entanglement

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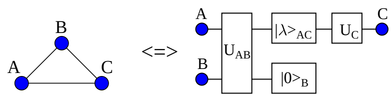

FIG. 1: Decomposition of a pure three-mode Gaussian state. $|\lambda\rangle_{AC}$-two-mode squeezed vacuum; $|0\rangle_B$-vacuum state, U_{AB}, U_C-unitary transformations governing in Heisenberg picture linear canonical transformations of quadrature operators.

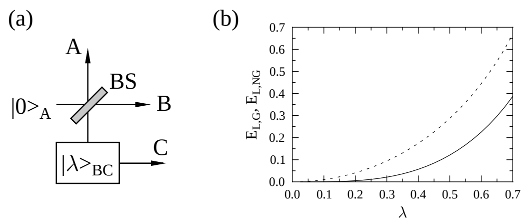

FIG. 2: (a) Scheme for preparation of a three-mode Gaussian state. (b) Maximum logarithmic negativity $E_{L,G}$ (solid curve) for optimal Gaussian measurement on mode C and average entropy of entanglement $E_{L,NG}$ (dashed curve) for measurement of photon number on mode C versus squeezing parameter λ.

Multipartite entanglement is a resource for one-way quantum computing [1] and quantum teleportation network [2]. For applications in quantum communication it is imperative to know how much entanglement can be localized between two parts A and B of the multipartite entangled state by local measurements on the remaining parts $\mathbf{C}$ and classical communication of the measurement outcomes to A and B. This the so called localizable entanglement was originally studied in the context of two-dimensional quantum systems [3].

We investigated the problem of localizable entanglement for Gaussian states of quantum systems with infinitely-dimensional Hilbert spaces [4]. First, we considered pure states of three modes A, B and C and we used entropy of entanglement to quantify the amount of entanglement localized between modes A and B by Gaussian measurement on mode C. Decomposition of the state depicted in Fig. 1 has led to the finding that maximum entanglement is localized by homodyne detection on mode C. Based on this result we further showed that also for N-mode pure Gaussian states homodyne detection on $N-2$ modes C_k, $k = 1, \ldots, N-2$ maximizes entanglement between the remaining modes A and B.

Next we studied localizable entanglement for mixed N-mode Gaussian states which are invariant under arbitrary permutation of mode and we employed the logarithmic negativity as an entanglement measure. Reducing the problem to the three-mode problem by expressing the state as an interference of a two-mode state and $N-2$ single-mode states on an array of beam splitters we proved that the logarithmic negativity is again maximized by homodyne detections on modes $\mathbf{C}$.

Finally we have shown on a particular example in Fig. 2 that if we allow a non-Gaussian measurement we can localize more entanglement than we can localize by optimal Gaussian measurement.

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Optimal asymmetric cloning and non-unity gain partial estimation of coherent states with linear optics

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Optimal estimation and copying of quantum states are important primitives useful for many quantum information processing applications. It is well known that it is impossible to perfectly copy or estimate nonorthogonal quantum states. It is, nevertheless, possible to accomplish these tasks approximately and optimize the performance of the devices such that the fidelity of cloning or state estimation is maximum possible.

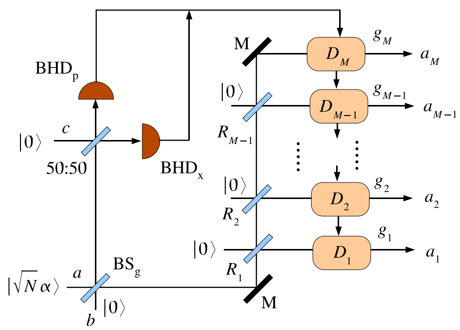

FIG. 1: Optimal multicopy asymmetric cloning of coherent states.

In the context of quantum information processing with continuous variables, cloning and estimation of coherent states are of particularly high importance. The coherent states are readily available experimentally in the form of light beams emitted by lasers and are used in most continuous variable quantum cryptography protocols. The cloning or estimation of coherent states represent a simple yet relatively powerful means of eavesdropping on the quantum key distribution with coherent states. Any such eavesdropping inevitably adds some noise into the state transmitted to the authorized receiver, which lies at the heart of security of the QKD. It is thus important to study the trade-off between information gained and added noise.

Motivated by these practical considerations, we have proposed schemes for optimal multicopy asymmetric cloning of coherent states [1] and for optimal partial non-unity gain estimation of coherent states [2]. Both schemes rely on passive linear optics, homodyne detection and feedforward. The cloning setup is depicted in Fig. 1. The input signal is split in two parts on an unbalanced beam splitter, one part is sent to eight-port homodyne detector and the other part is split among M output modes using an array of unbalanced beam splitters. Each mode is then displaced by an amount proportional to the measurement outcome and M copies with M different fidelities are thus produced. Optimal cloning is achieved by proper choice of splitting ratios and feedforward gains. The optimality can be proved by using semidefinite programming techniques [1].

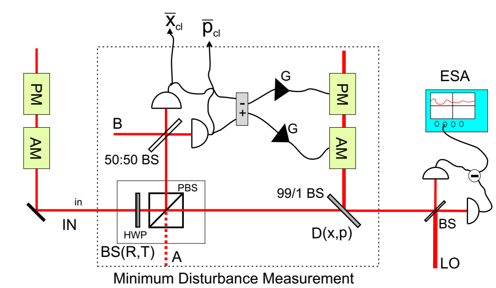

FIG. 2: Optimal partial non-unity gain estimation of coherent states.

The setup for optimal partial state estimation is shown in Fig. 2 and is similar to the setup for optimal cloning. The classical estimate of the input coherent state is obtained from the measurement results. Besides classical estimate, the device outputs also a quantum copy of the input state, whose coherent amplitude is amplified or attenuated by a variable gain g. For a given amount of noise added to the output quantum copy, the device minimizes the noise in the classical estimate. This optimal partial estimation of coherent states has been successfully demonstrated experimentally [2].

This work was supported by MSMT (projects MSM6198959213 and LC06007) and by the EU project COVAQIAL (FP6-511004).

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Distillation and purification of phase-diffused squeezed states of light

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Noise, decoherence and losses inevitably accompany any distribution of quantum states of light over realistic quantum channels such as optical fibers. These detrimental effects can mask or even completely destroy the neoclassical properties of transmitted light beams. However, ingenious techniques of quantum state distillation and purification have been devised to counteract such unwanted influences. The general idea behind such protocols is to extract from many copies of noisy states a single copy with increased non-classicality and purity.

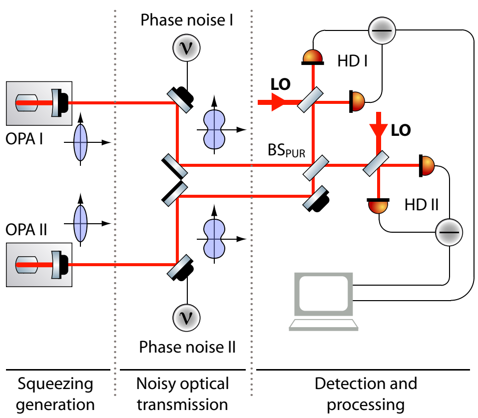

FIG. 1: Setup for purification of phase diffused squeezed beams. OPA - optical parametric oscillators, LO - local oscillator beams, HD - homodyne detectors, BS - balanced beam splitter.

We have focused on theoretical and experimental analysis of purification and distillation of squeezed states that suffer from phase fluctuations. The phase fluctuations transform the initially Gaussian states into non-Gaussian ones. This makes it possible to distill these states using only Gaussian operations, namely interference of two copies of the noisy state on a balanced beam splitter and conditioning on the outcomes of the trigger balanced homodyne detector HD1, see Fig. 1.

Building upon the results obtained in a previous year [1], we have performed a detailed theoretical as well as experimental analysis of the distillation setup. We have shown that, surprisingly, it is sometimes advantageous to use the originally anti-squueezed quadrature for triggering. Typical experimental results are shown in Fig. 2, together with theoretical predictions obtained from a simple analytical model [2]. The reduction of quadrature variance indicating increased squeezing is clearly visible. We have studied theoretically an iterative version of the distillation protocol and proved that the purity of the asymptotic Gaussian state to which the procedure converges is equal to the purity of the initial state before passing through the de-phasing channel [3].

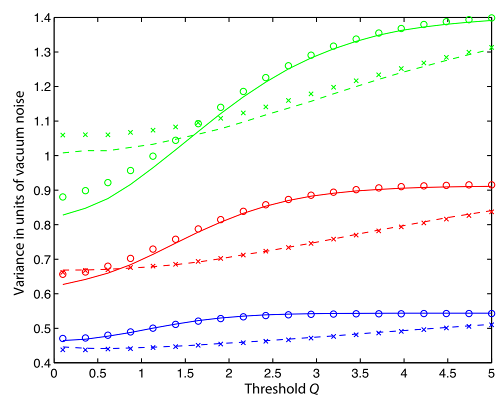

FIG. 2: Dependence of the squeezed-quadrature variance of the purified beam on the trigger threshold. Colors indicate three different levels of phase noise. Solid (dashed) lines correspond to triggering on measurements of squeezed (antisqueezed) quadrature.

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Path-phase duality with intraparticle translational-internal entanglement

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The aim of the research is to revisit the implications of complementarity when particles with internal structure prepared in special translational-internal entangled (TIE) states are sent into a Mach Zehnder interferometer (MZI). We show that such a TIE state permits us to find the phase shift in the MZI along with almost perfect path distinguishability, beyond the constraints imposed by complementarity on simultaneous which-way and which-phase measurements.

The quantum mechanics puts fundamental constraints on simultaneous knowledge of the path the interfering particle takes in the MZI and the contrast of the interference pattern. Our best possible knowledge of the path is quantified by the distinguishability of the ways D. For $D = 0$ we cannot say anything about the path at all, whereas for $D = 1$ we know the particle's path with certainty. The quality of the interference is described by the visibility (the contrast of the interference pattern) V. If we find $V = 0$ the pattern is totally flat (no phase dependence), and $V = 1$ means the sinusoidal pattern is fully modulated. The quantitative complementarity relation between D and V, answering the question "how large could be V for a given D?", that holds for non-TIE states, reads [1, 2]

$$D^2 + V^2 \leq 1. \tag{1}$$

In our paper [3] we have reformulated the above mentioned question to "how well can we distinguish between two close phases present in MZI for a given D?". The distinguishability of the phases is quantified by the sensitivity S [3], proportional to the phase derivative of the interference pattern. The S-D relation for non-TIE states is closely related to the V-D relation (see [3]), namely

$$D^2 + S^2 \leq 1, \tag{2}$$

whereas for TIE states is modified to

$$D^2 + \frac{\left(S - \frac{N-1}{2N}\right)^2}{\left(\frac{N+1}{2N}\right)^2} \leq 1. \tag{3}$$

Here N is a parameter specifying whether the relevant input state is the TIE state or not. For $N = 1$ we have standard state (no TIE) and for $N \neq 1$ we have TIE state. From (2), (3) and Fig. (1) we see, that TIE states, $N \neq 1$, allow for much better trade-off between S and D, hence better simultaneous which-way and which-phase distinguishability.

In the forthcoming year we plan to explore possible and feasible experimental realization of TIE states, different to that proposed in [3].

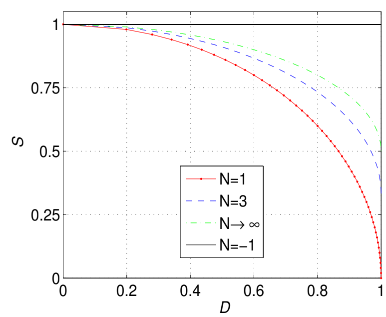

FIG. 1: The S-D relation (3) for various values of the parameter N, and a special case of $N = -1$, not captured by (3).

The work was supported by GAČR (GA202/05/0486), MŠMT (LC 06007), MSM (6198959213).

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Generation of the different types of the frequency correlations of entangled photon pairs

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The main goal of this project was to experimentally verify that the pulse-front tilt (PFT) technique can control the type of frequency correlations and the bandwidth of entangled photon pairs generated by spontaneous parametric downconversion (SPDC) in a nonlinear crystal pumped by femtosecond laser pulses. It allows us to produce frequency-correlated, anticorrelated and uncorrelated entangled photon pairs at will. The PFT technique is based on appropriate engineering of the group velocities of all interacting fields in a nonlinear medium [1, 2]. The experimental verification of theoretical prediction is done in paper [3] and experimental setup is shown in figure 1. The Ti:Sapphire femtosecond

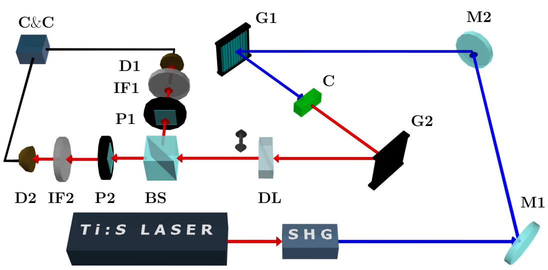

FIG. 1: The experimental setup.

laser emits light pulses at 810 nm wavelength with a 3.6 nm (FWHM) bandwidth which pass through a SHG unit where the pump beam is generated. The pump beam hits the first grating that applies appropriate pulse-front tilt. Diffracted pulses enter a 2mm thick BBO crystal where degenerate collinear type-II SPCD occurs and the second grating removes the angular dispersion of downconverted beam. The creation of highly frequency-correlated or anticorrelated entangled photons additionally restores the polarization entanglement of downconverted photons and therefore frequency correlations are measured in a Hong-Ou-Mandel (HOM) interferometer. The theoretical and experimental results can be seen in figure 2.

The main advantage of the PFT technique is that it can be used in any nonlinear material and at frequency bandwidths where standard solutions cannot be applied.

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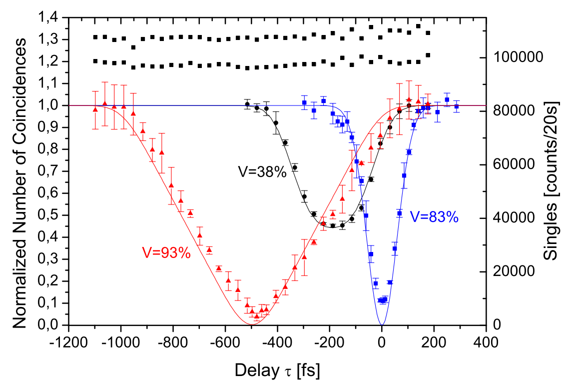

FIG. 2: The normalized number of coincidences and singles as a function of the time delay τ in a HOM interferometer. Black dot - no pulse-front tilt, red triangle - frequency-correlated photons, blue box - frequency-anticorrelated photons, black box - single counts, solid lines - theoretical prediction.

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Experimental realization of advanced vortex information channel

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Our research activity in the project is mainly focused on theoretical and experimental methods of optical communications enabling increasing information density by information encoding into the spatial structure of the composed vortex beams. In standard optical communications, the information code is created as a sequence of pulses representing two states (0 or 1). The mixed vortex states studied in the project enable insertion of additional information into the spatial structure of each pulse [1]. The basic principle of the vortex information encoding was proposed and examined during preceeding years. For the experimental verification of the method the spatial light modulators (SLMs) were used. This experiment approved functionality of the method but it is not directly applicable because of the expensiveness and relatively low repetition rate of the SLMs. During last year, an advanced method of the vortex information transfer was developed and examined. The activity resulted into the design of the vortex information channel enabling verification of the free-space vortex information transfer in laboratory conditions [2]. The principle of the advanced method of the information encoding and decoding is illustrated in Fig. 1. Information encoding is performed by means of the photolitographically prepared phase mask replacing the SLM used in the original set up [3]. The required dynamical regime is achieved by standard switching of beams illuminating the mask. The phase mask transforms the directionally separated beams to the pure vortex beams and deflects them into the same direction. The topological charges of the created vortex modes are distributed in dependence on the propagation directions of the beams impinging on the mask. The amplitude of the vortex modes are controlled by switching of the illuminating beams. By this way, the dynamically modulated mixed vortex beam carrying an actual information code is created. Information decoding is performed by means of the phase mask identical with that one used for the encoding process. By its action, the separate pure vortex modes splits into different directions and simultaneously the topology of their wavefront is changed. Amplitudes of the pure vortex modes carrying information are obtained after optically realized Fourier transform by direct intensity measurement of the detected signal. In the experiment (Fig. 2), the source illuminating the encoding mask was assembled by 4 switched laser diodes (635 nm, 5 mW). The phase masks used for information encoding and decoding were prepared photolitographically. They were realized as 8 level masks with 1500×1500 pixels at the area of $3 \times 3mm^2$. The transfer of information was realized with 4-dimensional base of vortices and demonstrated for free-space propagation on the distance of 6 meters [2].

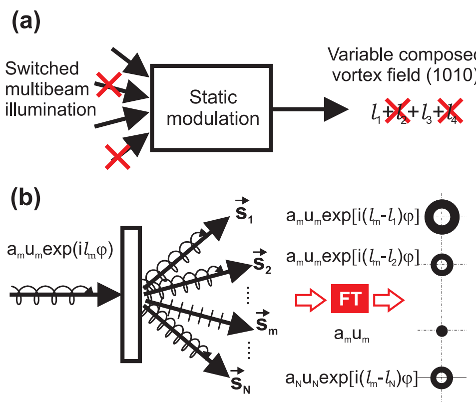

FIG. 1: Principle of the information encoding (a) and decoding (b).

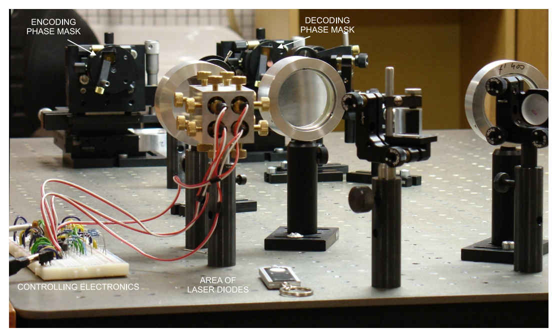

FIG. 2: Snapshot of the set up for vortex information transfer.

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Nonclassical light in nonlinear optics

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We have interpreted experimental data for mesoscopic twin beams from parametric down-conversion in terms of joint photon-number and integrated-intensity distributions [1] showing classical and quantum regimes, sub-Poisson behavior of conditional distributions and sub-shot-noise behavior of difference-number distribution. This description was extended for multimode processes to stimulated parametric down-conversion with similar illustrations [2]. Combination of optical parametric amplification with two-mode nonlinear Kerr effect can be an effective source of squeezed light [3]. Four-mode optical parametric process as a suitable combination of optical parametric amplification and frequency conversion is a source of light with reduced quantum amplitude and intensity fluctuations in various single and compound modes [4]. In future the results will be applied to available experimental data for their interpretation from the first principles.

The possibility of generating counter-propagating entangled photons by means of waveguide with the periodic nonlinearity has been studied [5]. Inspired by quantum mechanics, we have investigated several miscellaneous problems of mathematical physics [6–8].

In the future research we will elaborate several current topics of quantum optics: perturbation method for description of down-conversion in a waveguides, the theory of the recently proposed quantum degree of polarization and quantization of light in a lossless medium.

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Tomographic methods for quantum information processing

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The investigation of tomographic methods and quantum estimation was continued. Several important results were achieved and published in Refs. [1–4]. The current research is focused on the following main subjects:

- The development of new efficient algorithms for quantum-state reconstruction [1].
- The tomography of high-dimensional systems [2].
- The quantification of reconstruction errors [3].
- The application of these ideas to experimental characterization of complex systems [4].

As a major achievement of this group in 2007, the picture of self-consistent "objective tomography" was completed in publications [2, 3], see below.

The research on the formal aspects of quantum tomography delivered results in the formulation of new reconstruction algorithms and also in the interpretation of reconstruction results. An iterative likelihood-maximization procedure for quantum tomography was proposed [1], which is applicable when the standard iteration did not monotonically increase the likelihood. The new algorithm was tested on two sets of experimental data measured on photons and ions.

The formulation of quantum tomography as an objective technique that was started in [2] was completed in [3] and successfully applied to diagnostics of quantum objects. A simple and operational recipe for placing error bars on any quantity inferred from a tomography measurement was given. The new resolution measure was applied to quantum-optical homodyne tomography. Some non-classical aspects of quantum states, such as the negativity of the Wigner function at the origin were shown to be hardly detectable with the present technology unless a lot of prior information on the measured system is available. In the next step our measure will be adopted for designing optimized tomography schemes with resolution tuned to a particular purpose.

In the field of experimental quantum tomography we focused on a detailed investigations of the conjugated pair of angle and angular momentum observables [4]. Attention was paid to improved experimental determination of uncertainty relations. Rigorous uncertainty relations for angle and angular momentum were formulated based on dispersion as a correct statistical measure of angular error. Fundamental Mathieu states were identified as "intelligent" states minimizing the uncertainty product for angle and angular momentum. In this sense, the Mathieu states were shown to provide the optimal distribution of information between the two observables with possible applications in information processing. An optical test of the derived uncertainty relations was performed by using and improved optical setup utilizing spatial light modulators both for the beam preparation and analysis.

In the next year, the research will be continued by finding a suitable phase-space representation of vortex beams and developing alternative experimental schemes for precise measurements of the angular and angular momentum observables. They will be utilized in a full experimental characterization of multi-dimensional quantum states of photons with the help of objective tomography.

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

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A further improvement of experimental setups for the measurement of spatial correlations and correlations in the number of photons has resulted in better signal-to-noise ratios. A source of second-harmonic field has been constructed and used for the generation of fields with even photon numbers with a Poissonian envelope [1] using collinear geometry and spontaneous parametric down-conversion. Mandel parameter has been measured and super-Poissonian photon-number distribution recognized experimentally. The obtained value of Mandel parameter has been in agreement with a low overall detection efficiency of the setup.

Photon-number statistics of optical fields composed of tens of photon pairs per mode have been measured and analyzed in collaboration with the group of Prof. Andreoni from University of Insubria in Como, Italy [2]. Phase-space quasi-distributions have been determined with the help of a microscopic quantum theory. Negative values and typical oscillations in quasi-distributions of integrated intensities have been observed. Sub-Poissonian conditional photon-number distributions and sub-shot-noise correlations in the difference of photon numbers have been derived as well.

New sources of photon pairs have been investigated. The generation of entangled photon pairs from nonlinear multilayers based on GaN/AlN has been experimentally investigated in collaboration with Prof. Sibilia from University La Sapienza in Rome, Italy [3]. A structure providing entangled photon-pairs with an anti-symmetric two-photon spectral amplitude has been analyzed theoretically [4]. Photons comprising such photon pair are perfectly anti-correlated when impinging simultaneously at a beam-splitter and moreover they are temporally anti-bunched. These states are prospective for future information protocols. Also waveguiding geometry with counter-propagating signal and idler fields and nearly perpendicular pumping as a source of photon pairs has been studied in detail [5]. This geometry has a wide range of tuning possibilities. It has been shown that both strongly entangled as well as separable two-photon states can be obtained from this source of photon pairs. Entanglement in photon pairs has been quantified using Schmidt decomposition of spectral two-photon amplitudes.

An eight-channel photon-number resolving detector based on single-mode fibers has been innovated and optimized [6]. Also a multimode variant of this detector has been built and tested. However, the multimode construction is accompanied by many difficulties like accidental interference that outweight its advantage of the lower level of losses.

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The group of statistical and wave optics in 2007

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Recent knowledge of physics enables one to develop noninvasive methods of velocity measurements. These methods can be classified mainly into two categories: methods using sound waves and optical methods. In the field of optics the utilization of a speckle pattern correlation method for detection of an object's in-plane velocity in a tangent direction of the diffusely reflective surface under investigation is presented [1]. This research work gains from knowledge obtained during measurement of the translation component [2] of the small deformation tensor. Numerical correlations of speckle patterns recorded periodically by a linear Complementary Metal Oxide Semiconductor (CMOS) detector during motion of the object under investigation give information used to evaluate object in-plane translations between each two consecutive records of the speckle patterns in different time instants. Knowledge of acquisition rate and the object in-plane translations is used to evaluate the object's velocity and then reconstruct its velocity profile. Designed experimental arrangement enables one to detect the velocity within the interval $(10 - 150)\,\mu\mathrm{m} \cdot s^{-1}$.

Next the research into the speckle correlation method running up to now resulted in design of device for noncontact detection and quantitative evaluation of movement of the human eyeball [3]. This device is useful for general physical objects, too.

Research into modification of properties of a speckled speckle generated by diffractal is under way [4]. The presented results show possibility to influence properties of the resulting speckle field. The future research into the area will concentrate on study of modified correlation properties of the speckle pattern.

White-light interferometry when measuring on optically rough surface do not resolve the lateral structure of the surface. It means that there are height differences within one resolution cell that exceed one fourth of the wavelength of the used light. Thus the following questions arise: What height is then measured by white-light interferometry? How affects the surface roughness the measurement uncertainty? These questions form the basis of our research. We try to find the answers by means of numerical simulations. However before the abovementioned questions can be answered, the distribution of the intensity of individual speckles and the influence of roughness and of the spectral width of the used light source on the decorrelation of white-light correlogram are discussed [5].

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