Annual Report 2008

Measurement and Information in Optics

MSM 6198959213

and

Center of Modern Optics

LC06007

The Annual Report 2008 covers all the scientific activities of 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.

Olomouc, January 2009

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Noise in quantum communication and information processing

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In 2008 year, the research in this direction focused on following projects:

CV QKD with noisy states. It was an important break through when pure coherent laser light was found to be a sufficient resource to generate a secret key, even through an arbitrarily lossy channel. In our work, a security of the continuous-variable quantum key distribution with noisy coherent states is discussed [1]. If the prepared states are directly transmitted through the lossy channel, an excess noise in the state preparation can prevent the secure key distribution. As we have shown, an arbitrary excess noise can be sufficiently reduced by a Gaussian purification after the state preparation. As a result of the purification, the key secure against both the individual and collective attacks can be always generated through arbitrarily lossy channel. A plan for 2009 year is more deeply investigate a role of noise in the encoding of realistic protocol and extend this to the protocol based on entangled states.

CV QKD through amplifying channel. It has been proved that the security of coherent-state key distribution against the collective attacks is preserved through any purely lossy channel if the reverse reconciliation is applied. A break of the security can occur only if an excess noise is presented in the channel. As a further progress, the coherent-state key distribution through Gaussian phase-insensitive amplifying channel is analyzed [2]. The amplification in the channel can occur, for example, from quantum erasing in the channel performed by third party or another quantum processing of transmitted key. The security is investigated under rather general assumption of any collective attack. The analysis says that for any noise-less amplification in the channel, the security is preserved if the direct reconciliation protocol is applied, at opposite to the purely lossy channel. A plan for 2009 year is to apply this analysis to quantum erasing error correction scheme.

Upload to noisy CV quantum memory. In this project, the noise excess free version of deterministic record of unknown quantum state into the quantum memory is described and the probabilistic upload of highly non-classical states (single-photon state, superposition of coherent states) approaching lossless light-atomic transfer is proposed [3]. It is shown that the original set-up of continuous-variable can be directly used to reach the noise excess free deterministic record (up to the squeezing) of any quantum state of light. It can be achieved for an arbitrary weak quantum non-demolition coupling and without any noise pre-squeezing of the state of atomic memory. Unfortunately, the application of the deterministic squeezing post-correction is always at a cost of an additional attenuation. Therefore, a probabilistic upload is proposed based on a post-selection of the measurement results from the homodyne detector placed in this memory set-up. It is proved that the single photon can be probabilistically uploaded into the memory with arbitrary small loss and with an arbitrary high fidelity. The superposition of coherent states can be probabilistically uploaded with a reduced amplitude, but with the purity approaching unity. A plan for 2009 year is to investigate an application of quantum memory in the production and transmission of the entanglement. Further, noiseless non-local quantum operations on two distant memories will be investigated.

Quantum adaptation of noisy qubit channels. In this project, the adaptation of quantum channels is proposed to prevent the break of entanglement [4]. The probabilistic adaptation differs from the single-copy entanglement distillation and purification. In the adaptation, even in the case that the entanglement could not be increased by single-copy distillation after first channel, still the entangled state can be better prepared to the subsequent channel to preserve entanglement. As will be demonstrated, it can help to stop the sudden death of entanglement when the single-copy distillation is inefficient. A plan for 2009 year is to investigate quantum adaptation for the elementary single qubit noisy channels and novel method how to stop the break of entanglement using partial quantum control of quantum channel.

This work was supported by the Research Project of the Czech Ministry of Education "Measurement and Information in Optics" MSM 6198959213 and No. LC06007 of the Czech Ministry of Education and project No. 202/07/J040 and 202/08/0224 of GACR. R.F. also acknowledges a support by the Alexander von Humboldt Foundation and EU grant FP7 212008 - COMPAS..

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[4] M. Gavenda and R. Filip, Phys. Rev. A **78**, 052322 (2008).

Quantum information experiments based on fiber optics

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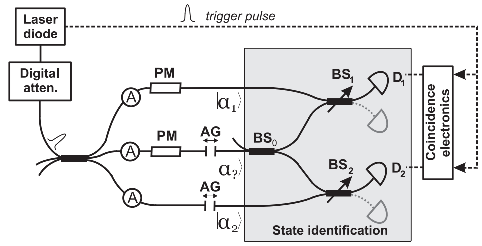

FIG. 1: Scheme of the setup for unambiguous discrimination of coherent states.

In this subproject we are focused on optical-fiber implementations of various procedures from the field of quantum information processing. It means that experimental setups are mainly built using optical fibers and fiber components.

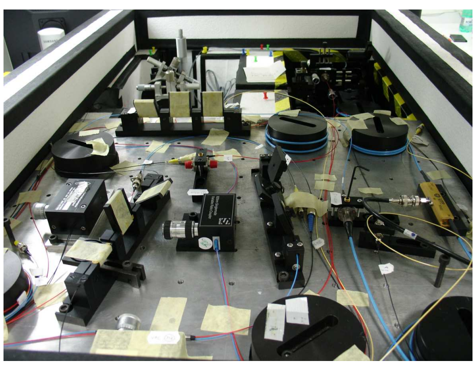

FIG. 2: Part of the experimental setup for post-selection reduction of noise thermally isolated in a polystyren box.

At the beginning of the year we finished experiment realizing an unambiguous discrimination of weak coherent states. Coherent states were prepared by attenuating a signal from a pulse laser by several orders. We investigated the basic implementation of a discrimination protocol where an unknown coherent state can equal to two different states, program states. The unknown state interferes with the two program states. According to clicks of two output detectors we can unambiguously conclude to which of these program states the unknown state is equal. Since the operation is probabilistic we have measured probabilities of correct identification for number of combinations of program states [1, 2].

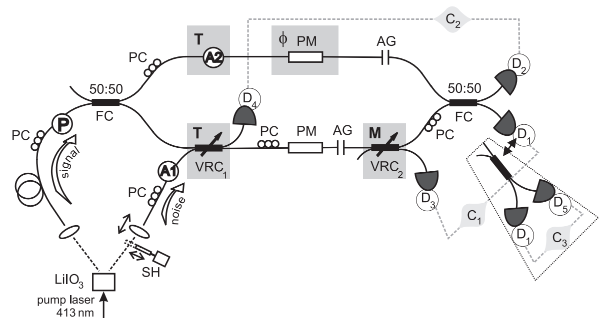

FIG. 3: Scheme of the setup for post-selection reduction of noise.

During the year we built a new setup implementing post-selection reduction of noise. In this experiment the source of entangled photon pairs generated by type-I parametric process was utilized. One photon, signal photon, from each pair interferes in Mach-Zehnder (MZ) interferometer. The other photon, noise photon, is added to one arm of this interferometer as a noise, more or less correlated with the signal. We investigate the influence of the noise on the visibility of interference at outputs of MZ interferometer. Moreover we investigate a possibility of increasing of this visibility by an additional postselection measurement.

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[3] L. Bartůšková *et al.*, Several experimental realizations of phase-covariant quantum cloning machines (poster), *Solvay Workshop "Bits, Quanta, and Complex Systems: modern approaches to photonic information processing"*, Brussels, Belgium, 29.4. - 3.5. 2008.

Experimental realization of programmable quantum gate

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We experimentally demonstrate a programmable single-qubit quantum gate. This quantum processor applies a unitary phase shift operation to a data qubit with the value of the phase shift being fully determined by the state of a program qubit. This is a striking feature of demonstrated programmable quantum gate because information on ϕ is faithfully encoded into *a single* quantum bit. Note that an exact specification of the phase shift ϕ would require infinitely many classical bits. The theoretical success probability of the protocol for our experimental realization is 25%.

Our linear optical implementation is based on the encoding of qubits into polarization states of single photons, two-poton interference on a polarizing beam splitter, and measurement on the output program qubit. The

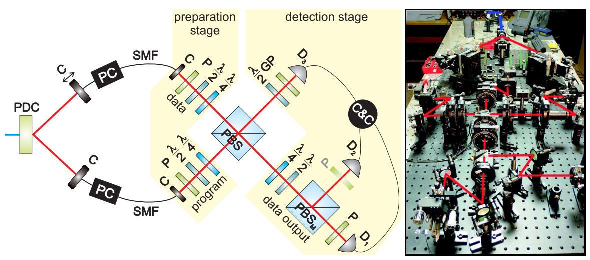

FIG. 1: Scheme of the experimental setup.

experimental setup and picture of setup are shown in Fig. 1. The correlated photons generated in the process of spontaneous parametric down-conversion serve as the program and data qubit. After being prepared in proper polarization states the photons interfere on the polarizing beam splitter (PBS). The detection stage consists of polarization analysis, single-photon detectors (D), coincidence logics and counting module (C&C). For polarization setting and analysis the fiber polarization controllers (PC), half-wave plates ($\frac{\lambda}{2}$), quarter-wave plates ($\frac{\lambda}{4}$), polarizers (P), Glan polarizer (GP), and polarization beam splitter (PBS_M) are used. According to simple theoretical model, taking into account imperfections of the PBS, the achievable average process fidelity is 97.7%.

We have characterized the programmable gate by full quantum process tomography. The achieved average quantum process fidelity exceeding 97% illustrates very good performance of the gate for all values of the encoded phase shift see Fig. 2. We also have estimated fixed phase offset $\delta\phi$ imposed by PBS and show that by using a different set of program states the device can operate as a programmable partial polarization filter with attained fidelity over 97%. More details about this experimental realization of programmable quantum gate can be found in work [1].

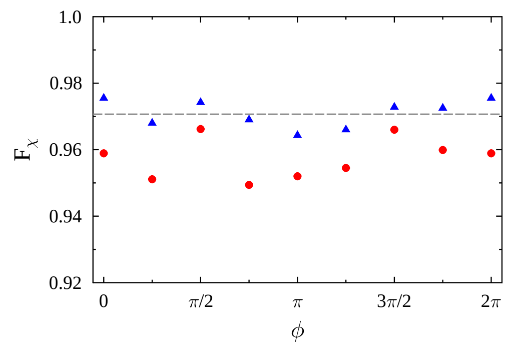

FIG. 2: Quantum process fidelity of the programmable gate is plotted as a function of the encoded phase shift ϕ. The fidelities before (●) and after (▲) compensation of the constant phase offset $\delta\phi$ are shown. The dashed line represents the best constant fit to the compensated fidelity data with the value of 97.1%.

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Quantum information experiments based on bulk optics

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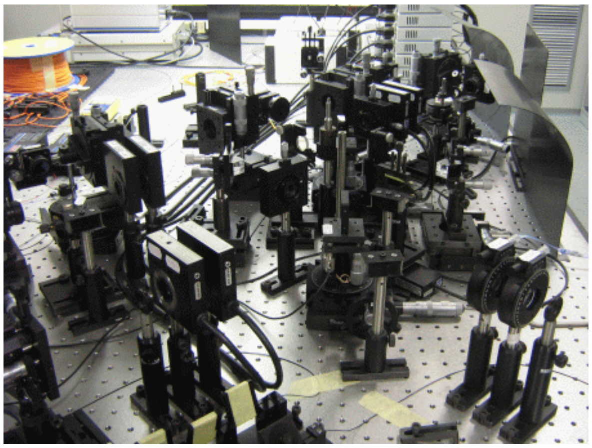
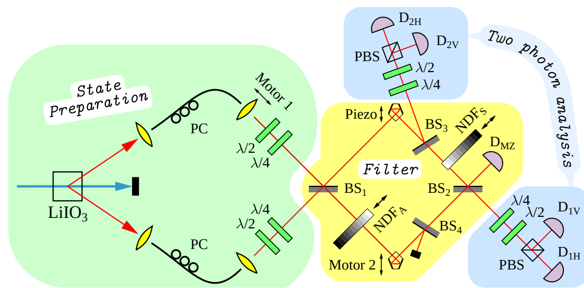


Obrázek 1: Picture of the key part of the universal quantum filter.

Experimental activities of this part of the project deal with quantum information processing, where the information content is encoded into polarization states of single photons. For this purpose bulk optics is used, which is more convenient than fibers. Pairs of time-correlated photons used in the experiments are generated by type-I parametric down-conversion. Polarization states are set by means of wave plates and polarization analysis is performed using pairs of wave plates, polarization beamsplitters and single-photon detection.

This year we finished works in the field of the phase-covariant cloning of the unknown quantum state. The very last results of all experiments with asymmetric cloning were summarized in Ref. [1].



Obrázek 2: Scheme of the universal quantum filter.

We continued with construction of linear-optical two-photon quantum gates and quantum filters. As a first subject we implemented a partial $SWAP$ gate [2]. 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.

After these measurements we rebuilt the setup according to Figs. 1 and 2. We added variable neutral density filters to both interferometer arms. This modification allows operation of the gate as a partial symmetrization or anti-symmetrization filter. Reconstruction of output states and full process tomography proved very good performance of the filters [3]. Our recent results were presented at several conferences as posters [4, 5], and talks [6].

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Path and phase determination for interfering photon with orbital angular momentum

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In our research summarized in [1] we deal with a possible optical realization of Translational-Internal Entangled (TIE) states [2] based on polarized photons with well-defined orbital angular momenta (OAM).

In [2] we have shown that under some restrictions on the evolution of a two-level system (evolution realized by TIE states therein) inside a Mach-Zehnder interferometer (MZI) the fundamental duality relation $D^2 + V^2 \leq 1$ [3, 4], is modified to [2]

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

where S, D quantifies our which-phase and which-way knowledge, respectively. A natural question arises on a feasible experimental proposal to test the theoretical predictions.

In [1], we have proposed an all-optical realization using polarized photons with well defined OAM [5]. The TIE states (representing the Which-Way detector [4]) basically undergo a unitary evolution

$$|1\rangle \to \exp{(i\phi)}|1\rangle,\ |N\rangle \to \exp{(iN\phi)}|N\rangle \tag{2}$$

inside each arm, with ϕ being the interferometric phase. We propose how to obtain similar evolution inside the optical MZI (see Fig. 1).

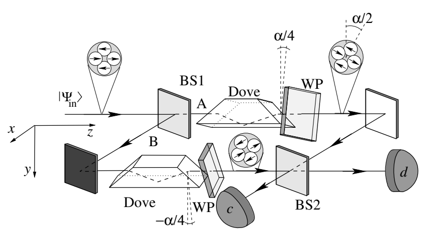

FIG. 1: Schematic plot of the interferometer proposed in [1]. An input state $|\Psi_{\rm in}\rangle = c_1|l\rangle|s=-1\rangle + c_2|l\rangle|s=+1\rangle$ is injected into the MZI, formed by two 50%-50% (non-polarizing) beam splitters BS1 and BS2 and two mirrors. After passing the rotated Dove prism and wave plate, the linear polarization is rotated by a different angle in each arm, depending on the angle of rotation α, according to (3). This resembles the desired evolution (2), and allows for which-way information by measuring the resulting photon polarization in certain basis by detectors (c) and (d) after BS2.

In our case the interferometric phase between the arms is changed not by means of changing the arm-lengths as usually (in contrast, we require the arm-length difference to be fixed) but by joint on-axes rotation of the Dove prism (DP) and wave plate (WP) inside each arm. This affects the phase of the interfering photon.

By rotating the Dove prism by an angle α (Fig. 1), the state of the photon with OAM $L = l\hbar$, denoted as $|l\rangle$, evolves to $|l\rangle \to \exp{[i2l\alpha]}|-l\rangle$. By rotating the WP by α, the spin (polarization) state $S = s\hbar$ ($s = \pm 1$), denoted as $|s\rangle$, of the photon evolves to $|s\rangle \to \exp{[i2\alpha]}|-s\rangle$. Hence, the overall evolution of the photonic total angular-momentum state, in one arm, reads

$$|l\rangle|s\rangle \to \exp{[i2(l+s)\alpha]}|-l\rangle|-s\rangle, \tag{3}$$

resembling the desired evolution (2) for two orthogonal circular polarizations ($s = \pm 1$), up to an unimportant swap of the basis states. The ratio of the phases acquired by the orthogonal circular polarizations (spin states) is $N \equiv (l+1)/(l-1)$. By choosing various l, we can vary N and obtain an analogy of (2), hence recover results derived in [2].

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

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Dynamical shaping of light for optical manipulation

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Our research activity in the project was mainly focused on theoretical and experimental methods enabling the real-time spatial shaping of coherent light. Subsequently, the mechanical effects of the dynamically shaped beams were studied and their application to optical manipulation was examined. We have developed and experimentally verified two different methods of the laser beam shaping based on the phase modulation of its complex amplitude and the spatial spectrum, respectively.

FIG. 1: Snapshot of the holographical laser tweezer.

In the former method, the coherent beam generated by the laser Verdi V2 (532 nm, 2W) was transformed by the Spatial Light Modulator (SLM) Boulder Nonlinear Systems (512× 512 pixels) and directed to the optical tweezer realized as an inverted microscope. The experiment enabled design and realization of the holographical laser tweezer in which a capture and relocation of mechanical objects was controlled by an interactive software. In the tweezer, the multiple optical traps can be created and the captured particles transported along trajectories defined in real-time by the mouse dragging.

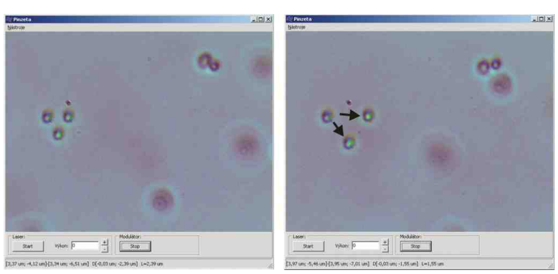

FIG. 2: Illustration of the required relocation of the particles in a multiple optical trap.

The later method of the dynamical laser beam shaping was based on the phase modulation of the spatial spectrum of the nondiffracting beam [1]. In the proposed and realized set-up, an axicon and optically addressed SLM were used to create multiple parallel Bessel beams and precisely control their positions in three dimensions. Experiment was realized at St. Andrews University. In the experiment, a possibility to utilize multiple Bessel beams for 3D positional control of trapped particles, active sorting of micro-objects or photoporation of living cells was approved. The proposed concept of experiment represents biophotonics workstation where users may trap and sort specimen using multiple optical Bessel modes.

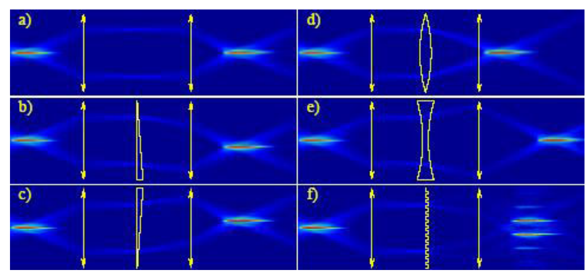

FIG. 3: Illustration of the beam shaping based on modulation of the spatial spectrum. (a) without modulation, (b) and (c) linear phase modulation (transverse relocation of the beam spot), (d) and (e) quadratic phase modulation (longitudinal relocation of the beam trail), (f) binary phase modulation (splitting of the input beam).

The method of spatial modulation of the Fourier spectrum of the Bessel beam was also employed in design and realization of the compact laser convertor [2]. The convertor was manufactured in Meopta Přerov and utilized for conversion of the diode laser beam or the fiber mode to the extremely narrow Bessel beam whose spot can be relocated across the plane perpendicular to the beam propagation direction. In performed experiments it was verified that the laser convertor is applicable to optical manipulation and enables transport of captured micro-objects along a desired trajectory [3].

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

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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. [1–5]. The current research is focused on the following main subjects:

- Quantification of reconstruction errors [1].
- Reconstruction of a quantum state of an unknown mode of light [2].
- Reconstruction of Gaussian states from homodyne data [3].
- Full reconstruction of vortex states [4].
- Experimental verification of uncertainty relations for vortex beams [5].

The research on the formal aspects of quantum tomography was continued by introducing a novel resolution measure for quantum tomography [1]. This measure was applied to quantum-optical homodyne tomography and it was shown that some non-classical aspects of quantum states, such as the negativity of the Wigner function at the origin might be undetectable with the present technology.

New tomography scheme was proposed capable of reconstructing the quantum state of an unknown mode of light [2]. It was shown that the complex mode structure of the investigated field could be expressed by a single number – the mismatch between the probe and signal. Simulations based on binary detection distinguishing only on/off signal proved that this procedure robust with respect to imperfections in the mismatch estimation. The proposed method opens new ways for reconstructions utilizing interference between independent sources.

In 2008 particular attention was payed to characterization of Gaussian states, which are building blocks of quantum information processing with continuous variables. Exploiting the formal analogies between the description of Gaussian states and that of finite-dimensional quantum states, a simple and efficient method for the reconstruction of Gaussian states was proposed and demonstrated [3]. The method was tested numerically and applied to the reconstruction of the quantum state of the signal generated by an optical parametric oscillator.

In the field of experimental quantum tomography we carried out a full program for the reconstruction of generic vortex states, including a complete phase-space description in terms a *bona fide* Wigner function [4]. The scheme determines the angular probability distribution of the state at different times under free evolution. To represent the quantum state we introduced a Wigner function defined on the discrete cylinder, which is the natural phase space for the pair angle-angular momentum. Uncertainty relations for this pair of conjugated variables were experimentally studied and verified in an experiment that employed computer-controlled spatial light modulators both at the state preparation and analyzing stages [5].

Results achieved in 2008 open the way for a full experimental characterization of multi-dimensional quantum states of photons in the next year.

This work was supported by projects of the Czech Ministry of Education "Measurement and Information in Optics" MSM 6198959213 and "Center of Modern Optics" LC06007 and project of the Czech Grant Agency No. 202/06/307.

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Schemes for linear-optics quantum information processing

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Linear-optics quantum information processing, which exploits encoding of qubits into polarization states of single photons and multiphoton interference to emulate nonlinear coupling between photons, has proved to be a very appealing and suitable platform for realization of various quantum information protocols. In our research we have focused of several important problems in this field and devised novel schemes for linear-optics quantum cloners and quantum gates. We have also suggested a procedure to generate an arbitrary multimode entangled state of two photons.

In particular, we have developed linear optical probabilistic scheme for the optimal cloning of a pair of orthogonally-polarized photons [1]. The scheme consists in a partial two-qubit symmetrization device realized with a modified unbalanced Mach-Zehnder interferometer, see Fig. 1, followed by two independent Hong-Ou-Mandel interferometers. This scheme has the advantage that it enables quantum cloning without the need for stimulated amplification in a nonlinear medium. It can also be modified so to make an optical two-qubit partial SWAP gate, thereby providing a potentially very useful tool to linear optics quantum computing.

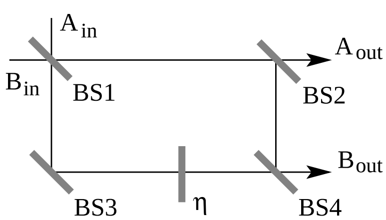

FIG. 1: Partial symmetrization of the polarization state of two photons. The scheme consists of four balanced beam splitters BS_j and one attenuator η.

We have also proposed a novel scheme for linear optical quantum Fredkin gate based on the combination of the linear optical partial SWAP gate and controlled-Z gates. Both heralded gate and simplified postselected gate operating in the coincidence basis are designed [2]. The suggested setups have a simple structure and require stabilization of only a single Mach-Zehnder interferometer. A proof-of-principle experimental demonstration of the postselected Fredkin gate shown in Fig. 2 appears to be feasible and within the reach of current technology.

Finally, we have developed a protocol capable of preparing an arbitrary state of two photons in several

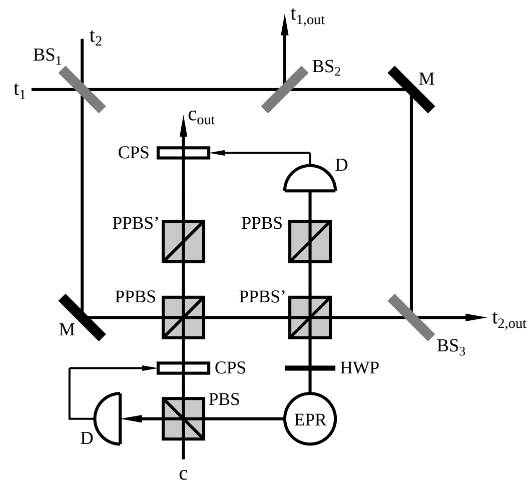

FIG. 2: Linear optical Fredkin gate operating in the coincidence basis.

spatial modes using pairs of photons generated by spontaneous parametric down-conversion, linear optical elements and single-photon detectors or post-selection [3]. The protocol contains several optimization capabilities with the goal of improving overall probability of its success. We have also shown how entangled two-photon states required for quantum computing with linear optics can be prepared using a very simple and feasible scheme.

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Time-multiplexed photon-number resolving detection

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Photon-number resolving detectors are capable to distinguish the number of photons in an incident light mode. Detection with photon-number resolution represents a crucial technique for many quantum optics applications, especially in the field of quantum information processing. Unfortunately, common on-off photodetectors such as avalanche photodiodes and photomultiplier tubes are not able to distinguish among photon-number states, even approximately in a limited range of photon numbers. Using several on-off detectors without photon-number resolution the photon-number resolving detector can be emulated. After dividing an incident light signal uniformly to several spatial modes they can be detected by an array of on-off detectors [1]. The number of used on-off detectors can be reduced by means of time multiplexing instead of the spatial one [2, 3].

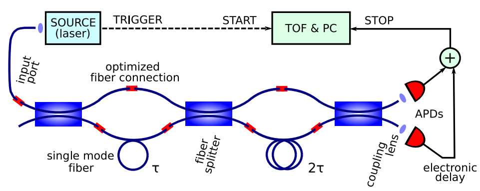

FIG. 1: Scheme of the eight-port photon-number resolving detector based on optical-fiber time-multipled device and a pair of on-off photodetectors with single-photon sensitivity. The basic element of the design is a fused 2×2 single-mode fiber splitter that divides an incident optical signal into two parts with approximately the same energy. After being divided the signal is delayed in one channel by time delay τ. The first output port of the splitter is directly connected to the next splitting stage while an optical fiber with a proper length is inserted at the output of the second port. The next splitting stage is constructed in the same way but with the time delay 2τ. Repeating the splitting stage three times the eight equidistant channels separated by time τ occur at the output, one half at the first output port of the last splitter and one half at the second one. The signals at the output ports are detected by two avalanche photodiodes (APDs), summed, and time-of-flight analyzed.

The goal of our work [4] is twofold. First the eight-port photon-number resolving detector is optimized for as small differences among relative probabilities of photon detection in individual output channels as possible. Non-ideal fiber splitters and other fiber components are used in a specific order and orientation which considerably improves the uniformity and makes the whole detector almost perfectly balanced. The measured relative detection probabilities of the detector channels yield the entropy $S = 0.9991 \pm 0.0045$ and the maximum deviation $\delta p = 1.25\%$ from the uniform distribution.

Further, the total detection efficiency of the detector is optimized by improving the transmittance T of the optical-fiber time-multiplexed device. The transmittance $(92.85 \pm 0.02)\%$ measured in our experiment can be compared to transmittance of 56% reached previously [3]. Using carefuly selected avalanche photodiodes the total detection efficiency of the detector reaches 65 % and the detector can be directly used to generate and measure highly nonclassical states of light.

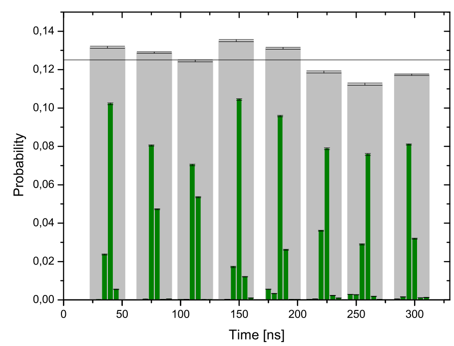

FIG. 2: Measured response function of the developed detector to weak coherent light pulses with Poissonian statistics with mean photon number of one photon per pulse at the input port of the detector. The eight distinct well-separated detection channels (light gray) are apparent in time-of-flight data. The detection probabilities of the particular channel span several 5 ns time-bins (green) due to the time uncertainty of the time-of-flight spectrometer and the source-detector jitter.

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Experimental entanglement distillation and concentration of squeezed states of light

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The distribution of entangled states between distant parties in an optical network is crucial for the successful implementation of various quantum communication protocols such as quantum cryptography, teleportation and dense coding. However, owing to the unavoidable loss in any real optical channel, the distribution of loss-intolerant entangled states is inevitably inflicted by decoherence, which causes a degradation of the transmitted entanglement. To combat the decoherence, entanglement distillation, which is the process of extracting a small set of highly entangled states from a large set of less entangled states, can be used. We have implemented two protocols for distillation and concentration of the deterministically prepared entangled squeezed light pulses that have undergone non-Gaussian noise. The first scheme allows to combat decoherence induced by a lossy channel, where the transmission is varying in time similarly to light propagation in the atmosphere. By employing linear optical components and classical communication, the entanglement is probabilistically increased [1]. The second protocol, depicted in Fig. 1, allows to suppress the noise induced by random phase fluctuations [2].

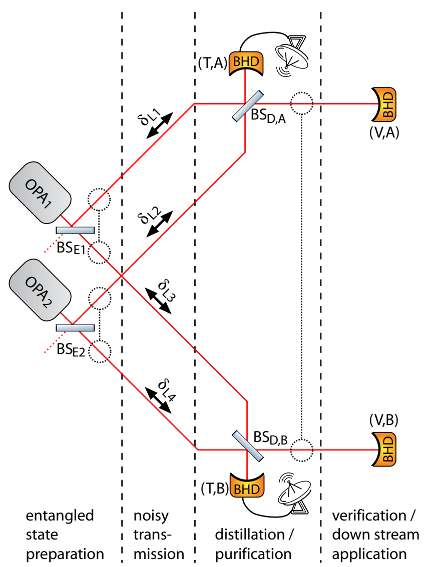

FIG. 1: Scheme for entanglement distillation of phase-diffused two-mode squeezed states.

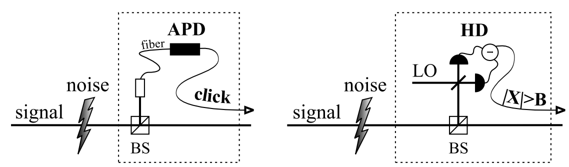

FIG. 2: Schematic illustration of a coherent state quantum filter for the non-Gaussian channel.

In a related study, we have also proposed and experimentally demonstrated nondestructive and noiseless filtering of vacuum states from an arbitrary set of coherent states of continuous variable systems [3]. Errors, i.e., vacuum states in the quantum information are diagnosed through a weak measurement, and on that basis, probabilistically filtered out, see Fig. 2. We considered several different filters and we found that on-off detection, optimal in the ideal theoretical setting, is superior to the homodyne strategy also in a practical setting.

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

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Three methods of processing data obtained from an iCCD camera have been elaborated and improved, namely one-threshold method, two-thresholds method, and method using statistical description of a detection event [1]. These methods serve for isolating noise in experimental data and giving the best information about real detection events [2]. A new iCCD camera detecting at 560 nm has been tested [3]; it provides about 3 times higher quantum detection efficiency compared to the older one. Software for processing raw experimental data from the camera has been designed. In parallel, measurement of absolute detection quantum efficiency based on pairwise character of the signal and idler fields has begun. Two schemes for obtaining absolute detection efficiency have been suggested and are going to be implemented experimentally and subsequently compared. A new variant of fiber-loop photon-number-resolving detector has been built and characterized [4]. It will be exploited in photon-number measurements during the next year.

Photon-number statistics in parametric down-conversion [5] as well as in a more complex process involving two $\chi^{(2)}$ processes have been measured and analyzed [6, 7]. Both iCCD cameras and ultra-sensitive photodiodes have been used. Experimental data have been analyzed along the model of multi-mode generalized superposition of signal and noise. Sub-shot-noise reduction in the difference of photon numbers has been demonstrated. Also quasi-distributions of integrated intensities have been derived and their behavior has been found to be non-classical [8, 9]. Especially, oscillations and negative values in these quasi-distributions have been revealed. The possibility of generating states entangled in photon numbers using post-selection from a three-mode state has been discussed and experimentally tested [6].

Model for the determination of an entanglement area has been developed [10]; it also includes pump-field parameters including waist width. Improvement in experimental setup that resulted in serious noise reduction has enabled to obtain high-quality data giving entanglement areas under different conditions. A good agreement between experiment and theory has been found [11].

This work was supported by research projects of the Czech Ministry of Education MSM6198959213, 1M06002, AVOZ10100522, and IAA100100713 of the Grant Agency of AS CR.

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

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Progress in the field of new sources of entangled photon pairs has also been reached. A detailed analysis of properties of photon pairs generated from a nonlinear waveguide with perpendicular pumping and counter-propagating signal and idler fields has been done [1]. Nonlinear layered structures with randomly positioned boundaries have been analyzed. Very narrow signal and idler field emission spectra represent their most striking feature. Because of spectral narrowness, signal and idler photons are nearly un-entangled. However, photon pairs generated at different emission angles can be superposed and new states interesting, e.g., for quantum computation, can be obtained [2]. Also nonlinear surface effects at boundaries of two dielectrics have been studied using a new method for the description of spontaneous down-conversion [3]. It has been shown that nonlinear effects at boundaries enhance photon-pair generation rates under conditions that have been defined. These conditions are met in usual layered structures where enhancement by factor of 2 can be observed.

In theory, quantum statistical properties of a superposition of displaced two-mode vacuum and single-photon states have been obtained. Also superposition of squeezed displaced two-mode vacuum states and single-photon states have been studied determining intensity correlations, Cauchy-Schwarz inequality, quadrature squeezing, and quasi-distributions [4].

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The group of statistical and wave optics in 2008

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White-light interferometry measuring optically rough surface shows an error caused by surface roughness [1, 2]. This error has a statistical character and is nonzero even if the determination of the contrast maximum of the interferogram were completely accurate. The amplitude of light reflected from an optically rough surface consists of many contributions originating from the scattering centers within the optical resolution cell. That is why the image of the surface is speckled. The different heights of scattering centers provide that the individual contributions experience different optical paths. The different optical paths together with the different amplitudes give rise to the measurement error of the surface location.

The distribution of the error caused by surface roughness tends to the normal distribution with zero mean. The standard deviation of this distribution is the measurement uncertainty.

If the spectral width of the light source or the surface roughness exceeds a certain limit, the speckle pattern becomes decorrelated. The result of a decorrelated speckle pattern is a distorted interferogram.

In the case of undistorted interferograms, the measurement uncertainty is given by a known realation which has been determined analytically for quasi-monochromatic light. It shows up that this relation is valid even for large spectral widths. In the case of distorted interferograms, the measurement uncertainty can surprisingly assume smaller values than in the case of undistorted interferograms if the center of gravity is taken as the position of the interferogram. In this case the measurement uncertainty decreases with the increasing spectral width of the light source.

Modern physics or more precisely optics already allows to measure quantitative parameters of object with resolution smaller than one micrometer. In the area of speckle metrology a way [3] how to modify original speckle pattern correlation measurement method is designed. The way increases a sensitivity of detection of translation of speckle field up to the orders of the wavelength of used light. Hence the proposed modification of the method increases a sensitivity of measurement of components of a small-deformation tensor that describe the deformation state of the elementary area of object's surface under investigation.

Research in the area of fractal optics shows ways how to influence spatial distribution of a light beam at the required distance from a transparent filter by means of suitable choice of regular or random fractal transparent filter [4]. It is proved that a negative or spatial light modulator is possible to use as equivalent of the transparent filter and achieved diffraction patterns demonstrate again fractal properties.

When a diffractal encounters diffusely reflective object's surface a field with fractal properties arises [4]. According to [4] the random diffractals generated by fractals of different dimensions produce fractal speckles. As presented in [5] these fractal speckles have the same the first order statistics as an order speckle pattern. This result is important for another way of modification of the speckle pattern correlation measurement method from the point of view of change of its measurement resolution by fractal speckle.

Finally the research into the speckle correlation method running up to now also resulted in design of device for non-contact detection and quantitative evaluation of movement of the human eyeball [6]. This device is useful for general physical objects, too.

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