Annual Report 2009

Measurement and Information in Optics

MSM 6198959213

and

Center of Modern Optics

LC06007

The Annual Report 2009 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 - 2011** 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. The team member Mgr. Michal Mičuda was awarded by the Scopus Prize for young scientists for the 2009.

Olomouc, January 2010

Zdeněk Hradil
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coordinator of the project LC06007

Quantum information experiments based on bulk optics

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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 focused on the implementation of an adjustable quantum filter for partial symmetrization and anti-symmetrization [1] and its utilization for universal asymmetric quantum cloning [2]. The device itself was obtained by the modification of the previous setup for partial SWAP gate.

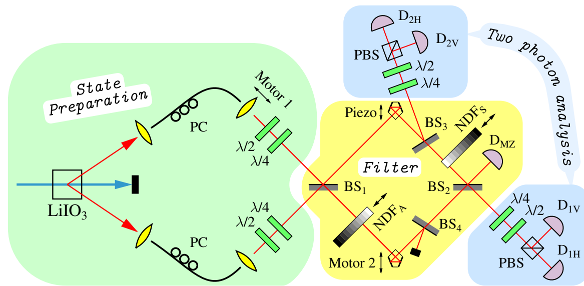

FIG. 1: Scheme of the universal quantum filter.

Our recent results were presented at several conferences.

[1] A. Černoch, J. Soubusta, L. Bartůšková, M. Dušek, J. Fiurášek, *Experimental implementation of partial symmetrization and anti-symmetrization of two-qubit states*, New Journal of Physics **11**, 023005 (2009) [IF=3.440].

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Universal quantum interfaces

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A high-fidelity transmission of quantum state from a source to a noisy target is a current problem in modern quantum physics. The quantum interface is a physical coupling between the source and the target, and it is ideally the unitary coupling corresponding to an interaction faster than all the simultaneous decoherence processes. For many targets, only a single kind of coupling is practically available. This fast coupling is typically weak; therefore the transmission through the interface has very low fidelity. Further, the target is often a hardly controllable system. It means, it can be only manipulated via this single interface. Together with a background noise of the target, typical for matter systems at a room temperature, it makes a high-fidelity transfer of unknown quantum state through this interface impossible. To be able to perform a full state transfer, we need actually two interfaces: (A) from the source to the noisy target and (B) inverse interface, from the target to the source.

We propose a novel method how to build an universal quantum interface from an arbitrarily weak Gaussian coupling converting an unknown quantum state between the source and the hardly controllable and noisy target. Using this method, the unknown state of the source is perfectly transferred to the arbitrarily noisy target for any strength of coupling. The interfaces are specifically proposed for both typical linear [1] and QND [2] interaction between the light and matter. The second one needs sequential or parallel combination of two identical QND couplings to achieve the goal. Also a probabilistic version allowing the perfect transfer without the feed-forward correction is discussed. This result shows proof-of-principle and feasible way of the high fidelity transfer of the quantum states of light to the collective matter (atomic, solid state) systems. The proof-of-principle experimental test of linear quantum interface based on classical correlation has been performed for the coherent states [3] and proposed for the squeezed states [4]. A following plan is to experimentally test basic properties of the all-optical processing for quantum interfaces in a collaboration with The Tokio University.

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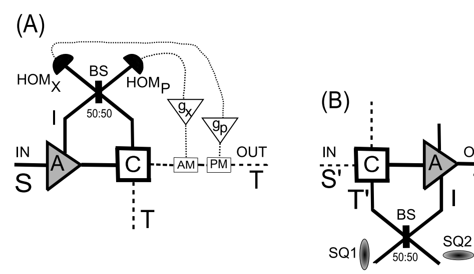

FIG. 1: (A) linear interface $S \to T$: A – phase-insensitive amplifier, C – linear convertor, BS – 50 : 50 beam splitter, HOM_X, HOM_P – homodyne detectors, g_X and g_P – gains of electronic amplifiers, AM and PM – amplitude and phase modulator. (B) linear interface $T \to S$: SQ1,SQ2 – orthogonal squeezed states of light.

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Engineering quantum states and operations

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Developing efficient and robust schemes for generation of highly nonclassical states of light and atoms and for implementation of various quantum operations on such states is essential for further advancement of quantum technologies such as quantum information processing or quantum metrology. Pursuing research along these lines, we have proposed several schemes for engineering quantum gates on light beams and for preparation of arbitrary quantum states of atomic ensembles.

We have proposed a linear optical scheme for the implementation of a three-qubit quantum gate that can be considered as a generalization of the two-qubit partial-SWAP gate [1]. The gate leaves unchanged all fully symmetric states of three qubits, and all states antisymmetric with respect to the transposition of some pair of qubits acquire a phase shift π. The gate operates in the coincidence basis and requires one auxiliary pair of photons prepared in the maximally entangled Bell state. By altering parameters of the proposed interferometric scheme, we can also obtain a quantum filter that attenuates amplitudes of the three-qubit states according to their permutation symmetry properties.

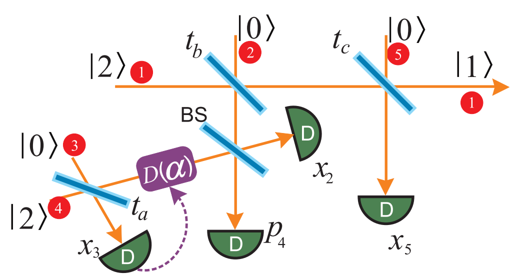

FIG. 1: Setup for generation of a single photon state from a pair of two photon states.

We have next investigated which non-Gaussian resources are needed, in addition to Gaussian operations and measurements, for implementation of arbitrary quantum gates on multimode quantum states of light [2]. We have shown that an arbitrary set of states with finite expansion in Fock basis is sufficient for this task. The key insight is that a single photon state could be generated from such resource state solely by Gaussian operations, c.f. example in Fig. 1.

We have also suggested an optical scheme for probabilistic implementation of an arbitrary single-mode quantum operation that can be expressed as a function of photon number operator [3]. The scheme coherently combines multiple photon addition and subtraction and is feasible with current technology. As concrete examples, we demonstrate that the device can perform approximate noiseless linear amplification of light and can emulate Kerr nonlinearity.

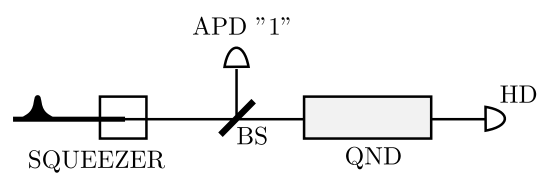

FIG. 2: Atoms-light interaction setup. A tiny portion of the light beam prepared in squeezed vacuum state is reflected from an unbalanced beam splitter BS and impinges on single-photon detector APD. Click of APD heralds subtraction of single-photon from the squeezed beam. Light in such state accompanied by orthogonally polarized strong coherent beam interacts with atomic ensemble. Afterwords, homodyne detection is performed on output light beam.

Finally, we have proposed an experimentally accessible procedure for conditional preparation of highly nonclassical states of collective spin of an atomic ensemble [4]. The quantum state engineering is based on a combination of QND interaction between atoms and light previously prepared in a non-Gaussian state using photon subtraction from squeezed vacuum beam, homodyne detection on the output light beam, and a coherent displacement of atomic state, see Fig. 2. The procedure is capable of non-deterministic preparation of a wide class of superpositions of atomic Dicke states.

This work was supported by MSMT under the projects Measurement and Information in Optics (MSM 6198959213) and Center of Modern Optics (LC06007) and by EU FP7 project COMPAS (212008).

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Tomography for analysis of Gaussian a vortex fields

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Full tomography from compatible measurements has been analyzed putting forward a reconstruction scheme prompted by the relation between a von Neumann measurement and the corresponding informationally complete measurement. This method is especially suited for the full tomography of complex quantum systems, where the intricacies of the detection part of the experiment can be greatly reduced provided some prior information is available. In broader terms this shows the importance of prior information in quantum theory. The proposed technique is illustrated with an experimental tomography of photonic vortices of moderate dimension [1].

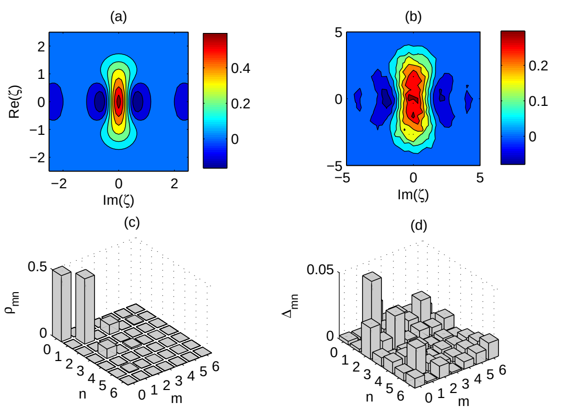

FIG. 1. Illustrating example of quantum state estimation in the presence of mismatch based on publication [3]. Panel (a): The true Wigner function for the signal Schrödinger kitten state ($\chi = 1$). Panel (b): "Stretched" point-by-point reconstruction for the true mismatch $\mu = 0.5$. Panel (c): True elements of the density matrix in the Fock-state basis for the signal Schrödinger kitten state of panel (a). Panel (d): Differences $\Delta_{mn} = |\rho_{mn} - \rho_{mn}^{true}|$ between the true ρ^{true} and the reconstructed ρ elements of the signal density matrix, $\mu = 0.5$.

A simple and efficient method for characterization of multidimensional Gaussian states was suggested and experimentally demonstrated. Our scheme shows analogies with tomography of finite-dimensional quantum states, with the covariance matrix playing the role of the density matrix and homodyne detection providing Stern-Gerlach-like projections. The major difference stems from a different character of relevant noises: while the statistics of Stern-Gerlach-like measurements is governed by binomial statistics, the detection of quadrature variances corresponds to chi(2) statistics. For Gaussian and near Gaussian states the suggested method provides, compared to standard tomography techniques, more stable and reliable reconstructions [2].

Finally we proposed a tomography scheme capable of reconstructing the quantum state of an unknown mode of light. The complex mode structure of the investigated field is expressed by a single number-the mismatch between the probe and signal. This opens up ways for reconstructions utilizing interference between independent sources [3].

The ongoing research will focus on the uncertainty relations for angular momentum operators, on the operational schemes for quantum tomography and on the analysis of Schack-Hartmann detection of the wavefront from the point of view of quantum tomography.

This document should address all the major activities supported by the Research Project "Measurement and Information in Optics" MSM 6198959213.

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Quantum logic gates programmable by single photons

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The primary focus of the project was to demonstrate logic gates programmable by single photons as building blocks of future quantum computers. Particularly, the phase-shift gate with single quantum bit (qubit) program and the sign-flip gate programmable by two-qubit entangled software have been developed. The former 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 [1]. The latter applies a sign flip operation to data qubit in an arbitrary basis fully specified by the entangled state of a two-qubit program register [2].

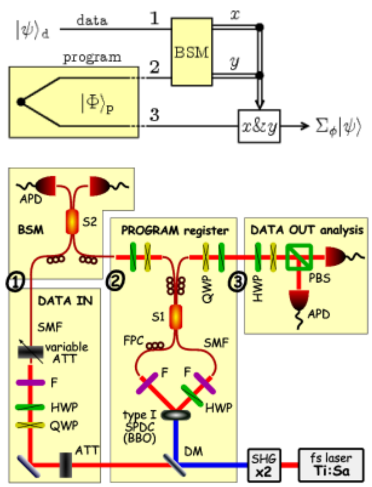

FIG. 1: Quantum circuit (upper panel) and experimental scheme (lower panel) for sign-flip programmable quantum logic gate. Qubits 2 and 3 form a program register prepared in a particular entangled state Φ_p. Bell-state measurement (BSM) is applied to data qubit 1 in an unknown quantum state ψ_d and qubit 2 of the program register. For singlet Bell state detected in channels 1 and 2 the measurement yields $x = y = 1$ which heralds the successful gate operation leaving the remaining qubit 3 in the target state. The unitary operation Σ_ϕ is determined by the state of the program register.

Our experimental implementation of the programmable logic gates is based on the encoding of qubits into polarization states of single photons, linear optics, multi photon interference, and coincidence detection. The sign-flip gate is built almost completely using optical fibers and couplers that enables trasferring the gate operation onto optical chip. The functionality of the new gates has been demonstrated with fidelity higher than 97% for single qubit program gate and 90% for two qubit program gate. The gates have been characterized thoroughly using quantum tomography.

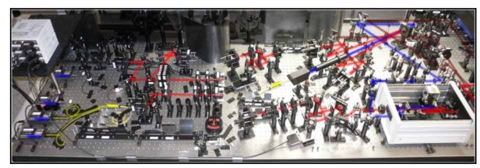

FIG. 2: Photo of the experimental setup used for quantum teleportation and sign-flip programmable quantum logic gate.

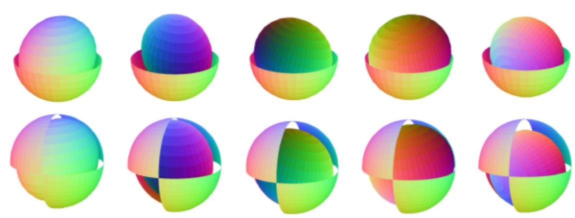

FIG. 3: Visualization of quantum teleportation (first column) and sign-flip gate for different program states. The outer shell stands for the input qubit and its various possible states represented by a color distribution. The inner shell visualizes the action of the gate by color changes depending on the program. Deformations come from experimental imperfections which degrade the gate operation.

The aim of the project in the long term is to fully exploit the potential of hyper-entanglement combined with single photon detection and electro-optic feedforward.

The work is supported by the Research Center for Modern Optics LC06007 and the Research Project "Measurement and Information in Optics" MSM 6198959213 of the Czech Ministry of Education.

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Gaussian entanglement distribution by separable states

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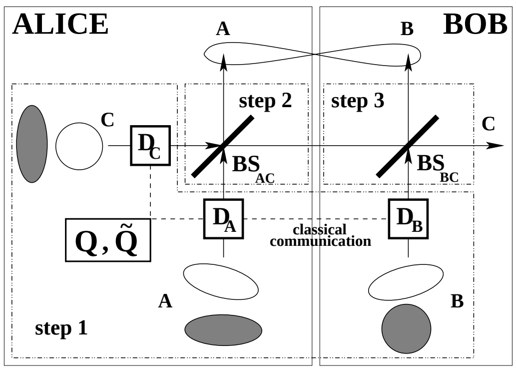

FIG. 1: Two schemes of the protocol for distribution of CV entanglement by separable Gaussian states. In the first scheme [2] (empty circle and ellipses) Alice's mode A and Bob's distant mode B are prepared in suitable rotated squeezed vacuum states while mode C is hold by Alice and it is in a vacuum state. In the improved second scheme [3] (hatched circle and ellipses) modes A and C hold by Alice are in the momentum and position squeezed vacuum states, respectively, and Bob's mode B is in a vacuum state. All the three modes are then displaced by displacements D_A, D_B and D_C distributed randomly with Gaussian distribution with covariance matrix Q ($\tilde{Q}$ for the second protocol) after which the modes are in a fully separable state (step 1). Mixing of modes A and C on a balanced beam splitter BS_{AC} entangles mode A with the pair of modes (BC) while mode B is separable from (AC) and mode C is separable from (AB) (step 2). Mixing of modes B and C on a balanced beam splitter BS_{BC} finally entangles A and B wile C still remains separable from (AB) (step 3).

Imagine two parties, Alice and Bob, in two distant laboratories. Suppose Alice holds a quantum system A and Bob a system B that are separable from each other. How can they entangle them without meeting each other in one place? Naturally, they cannot use local operations and classical communication (LOCC) to accomplish the task but instead they have to exchange another quantum system C. Strikingly, A can be entangled with B without C being ever entangled with (AB) as was shown for two-level systems (qubits) by Cubitt *et al* [1].

We show [2, 3] that such distribution of entanglement by a separable system is possible with Gaussian states of quantum systems with infinitely-dimensional Hilbert spaces, e.g., light modes. We propose two protocols in which two modes A and B of a fully separable three-mode Gaussian state become entangled just by interacting sequentially with the third mode C of the state on two balanced beam splitters. The proposed protocols consist of three steps and they are depicted in Fig. 1.

The amount of distributed entanglement is quantified by the logarithmic negativity $E_{\mathcal{N}}$ [4]. The first protocol allows to achieve up to $E_{\mathcal{N}} \approx 0.1165$ e-bits of entanglement which is further enhanced to $E_{\mathcal{N}} \approx 1.3334$ e-bits in the second protocol. The advantage of the protocols is that the challenging nonlinear controlled-NOT gates used in the qubit protocol [1] are replaced by simple beam splitters. Last but not least, the protocols are robust against weak isotropic noise in the initial state.

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