Optical quantum information processing

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MŠMT

Quantum resources for information processing

Superposition principle

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$$

Non-orthogonality of quantum states

$$\langle\phi|\psi\rangle = d_0^* c_0 + d_1^* c_1 \neq 0$$

Quantum correlations - entanglement

$$|\psi\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B\right)$$

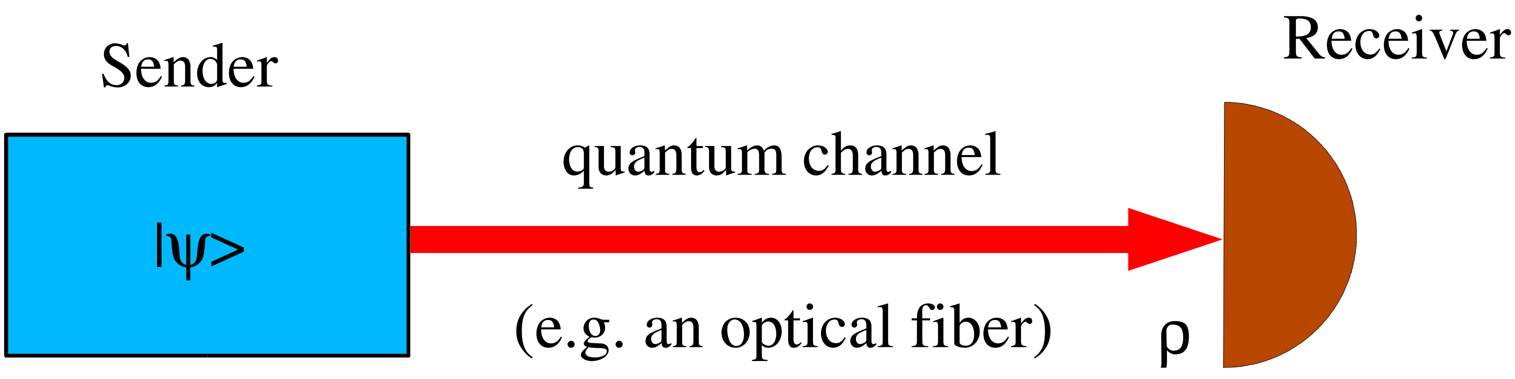
Main applications

- **Quantum cryptography**
  - provably secure distribution of a secret cryptographic key between two distant parties
- **Quantum computation**
  - fast factorization of large numbers (Shor's algorithm)
  - speed-up of search in an unsorted database (Grover algorithm)
  - efficient simulation of complex (e.g. solid state) quantum system

Quantum information processing

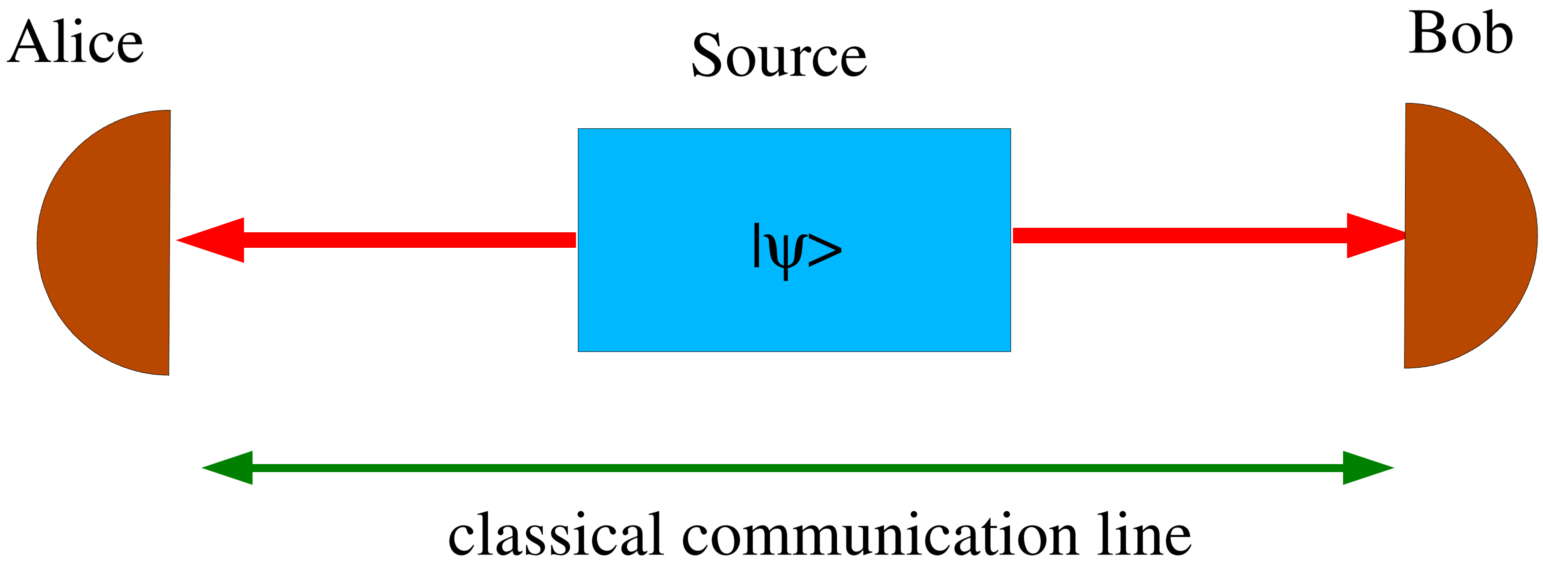
- **Quantum communication**
  - quantum cryptography
  - quantum teleportation
  - quantum dense coding
  - optimal quantum cloning
  - quantum state measurement and discrimination
- **Quantum computation**
  - design of quantum logic gates and computers
  - quantum algorithms

Optical quantum communication scenario



- **Sender –** encoding of information into quantum state of light beam
- **quantum channel** – transmission of the light beam over lossy nad noisy environment
- **Reciever** – measurement of the quantum state of the light beam

Entanglement-based quantum communication



- **Source –** prepares quantum correlated (entangled) state of two light beams
- this state is distributed to **Alice** and **Bob** who measure it
- A and B can also communicate over a classical channel

Discrete and continuous quantum variables

- **Discrete variables –** quantum bits, e.g. polarization state of a single photon

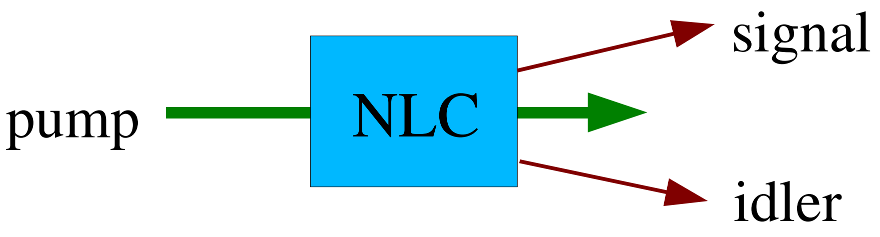
$$|\psi\rangle = c_V|V\rangle + c_H|H\rangle$$

- **Continuous variables –** information ecoded into quadrature operators of modes of the electromagnetic field or collective atomic ensemble

$$[x, p] = i$$

Quantum states of light

- **Coherent states –** produced by stable laser high above threshold
- **Squeezed states –** generated in the optical parametric amplifiers by the process of parametric down-conversion



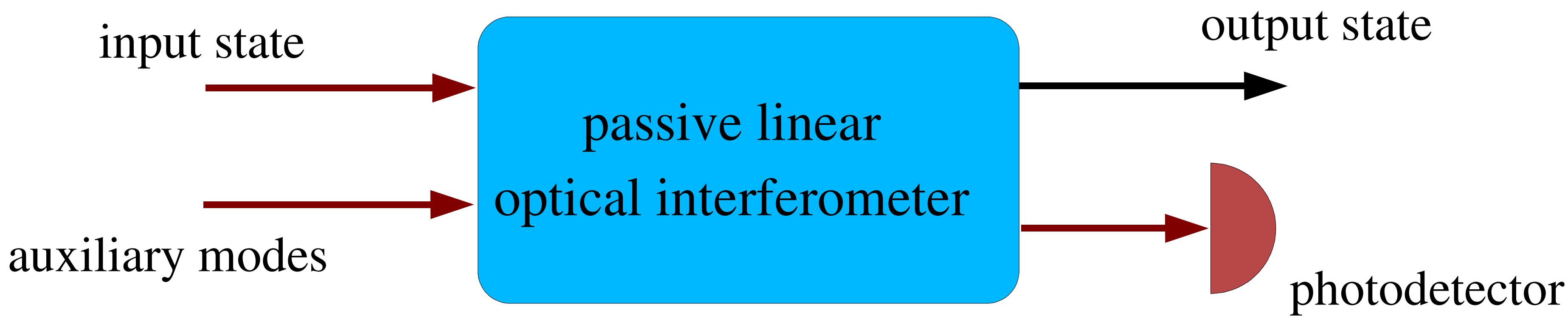
- **Correlated photon pairs –** generated in a nonlinear crystal pumped by a laser beam, again SPDC is exploited
- **Single-photon states –** can be prepared e.g. by conditioning on detection of a sphoton from the correlated photon pair

Our topics of research

- **Quantum state preparation**
  - generation of nonclassical and entangled states of light
- **Quantum state transmission, manipulation and distribution**
  - methods to suppress losses and decoherence in transmission
  - quantum memory for light, light/matter quantum interface
  - optimal quantum cloning
- **Quantum state detection**
  - optimal quantum state estimation and discrimination
  - programmable quantum measurement devices

I. Conditional quantum state preparation

Experimental preparation of non-classical states of light is limited by the lack of sufficiently strong nonlinearities at the single-photon level



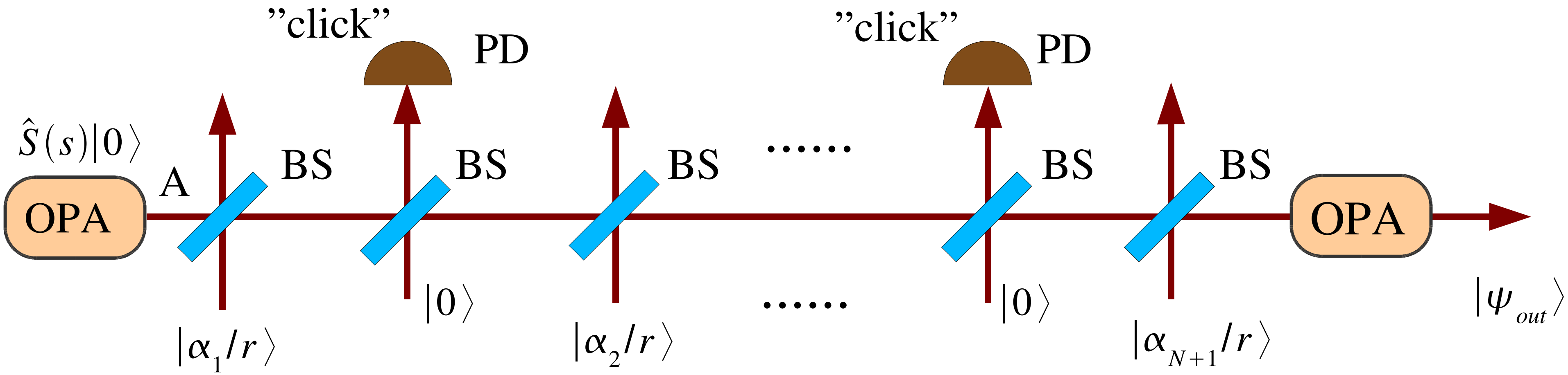
Possible solution – replace nonlinearity by quantum measurement and postselection conditioned on the measurement outcome.

Our main results

- **Scheme for conditional generation of arbitrary two-mode N-photon states**
- **Scheme for conditional preparation of arbitrary multimode states of traveling light beams using:**
  - sources of single photons
  - coherent states
  - passive linear optics
  - single-photon detectors
- **Scheme for generation of arbitrary single-mode states of light via photon subtraction from squeezed vacuum**

Generation of arbitrary single-mode state

- The quantum state engineering starts from single-mode squeezed vacuum
- A sequence of N+1 displacements and N single-photon subtractions is applied



The method allows to generate arbitrary superposition of the first N+1 Fock states

$$|\psi_{out}\rangle = \sum_{n=0}^{N} c_n |n\rangle$$

- A successful state preparation is heralded by clicks of all N detectors
- The coefficients can be controlled by varying the displacements

II. Quantum state distillation and purification

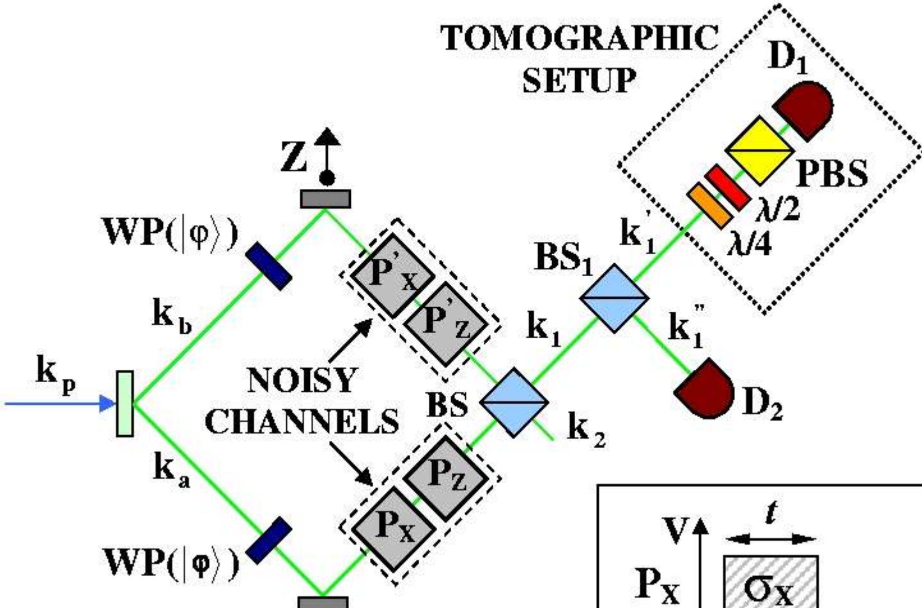
- Suppression of losses and decoherence which accompany quantum state distribution over realistic channels such as optical fibers

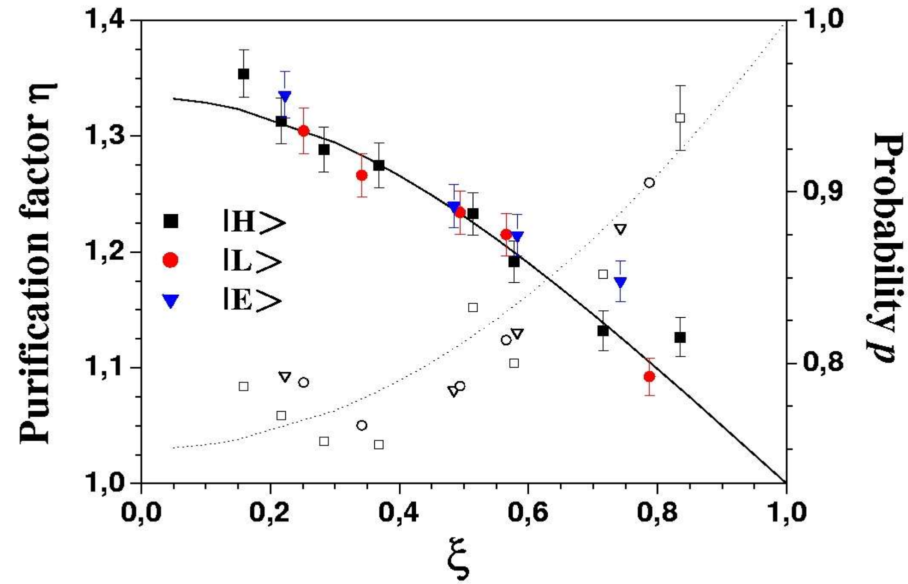
The method allows to extract few copies of states with high entanglemetnt, purity, squeezing etc. from many copies of mixed weakly entanlged or squeezed states

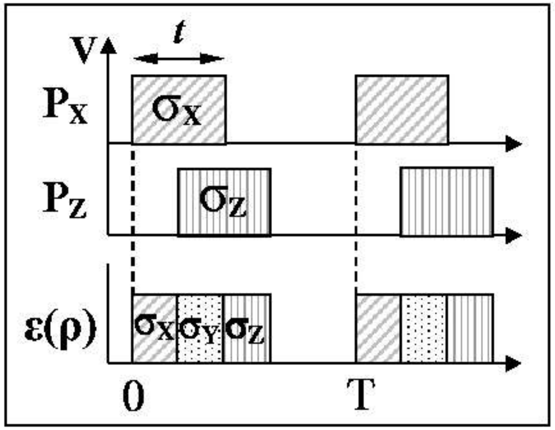
Our main results

- No-go theorem for purification of entangled Gaussian states via local Gaussian operations
- Protocol for concentration of CV entanglement using weak Kerr nonlinearity
- Purification of single qubits transmitted over depolarizing channel
- Purification of coherent states
- Distillation of phase-diffued squeezed states

Quantum state distillation and purification

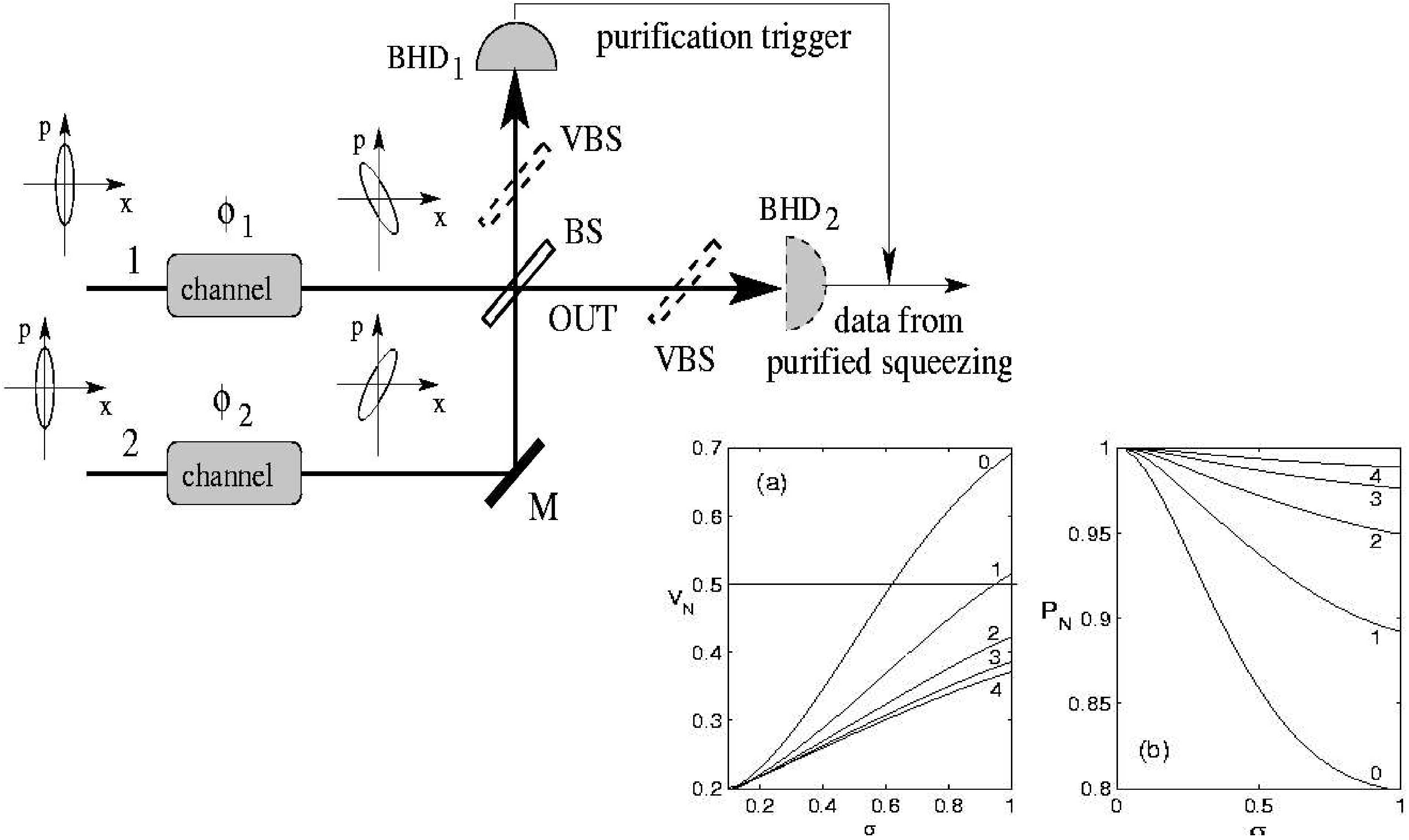






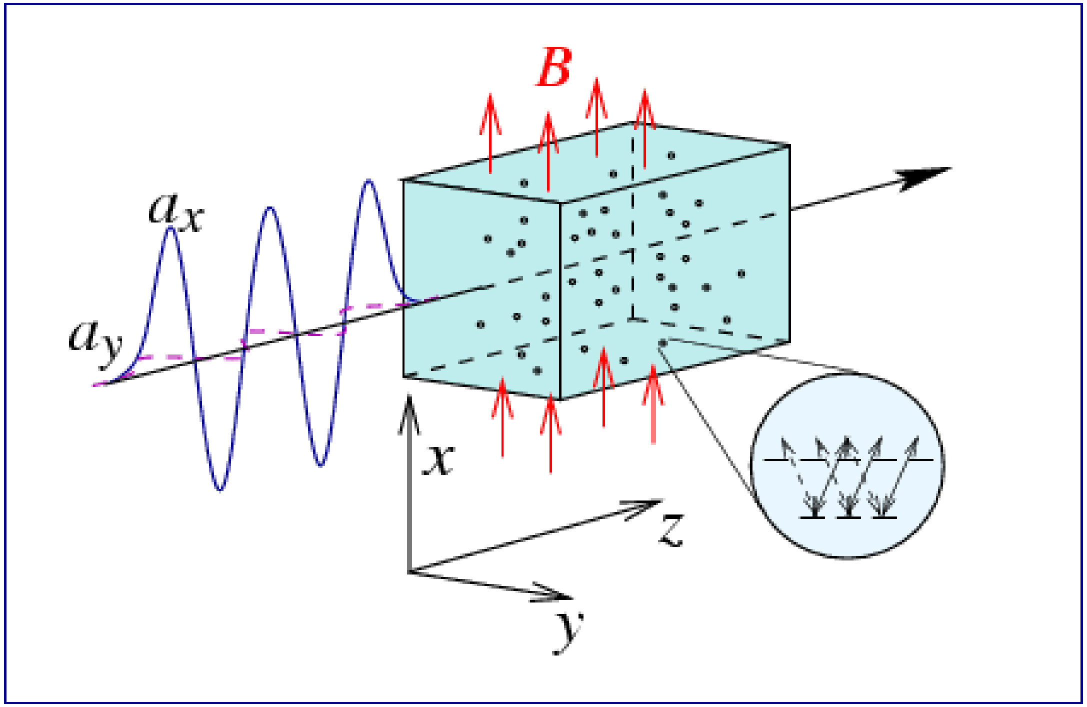
M. Ricci, F. De Martini, N.J. Cerf, R. Filip, J. Fiurášek and C. Macchiavello, *Phys. Rev. Lett.* **93**, 170501 (2004).

Purification of phase-diffused squeezed states



J. Fiurášek, P. Marek, R. Filip and R. Schnabel, submitted to PRL.

III. Light/matter quantum interface



Ensemble of 10^{12} Cs atoms held at a room temperature in a paraffin coated glass cell

Atomic spins are initially oriented along the x axis

B – magnetic field

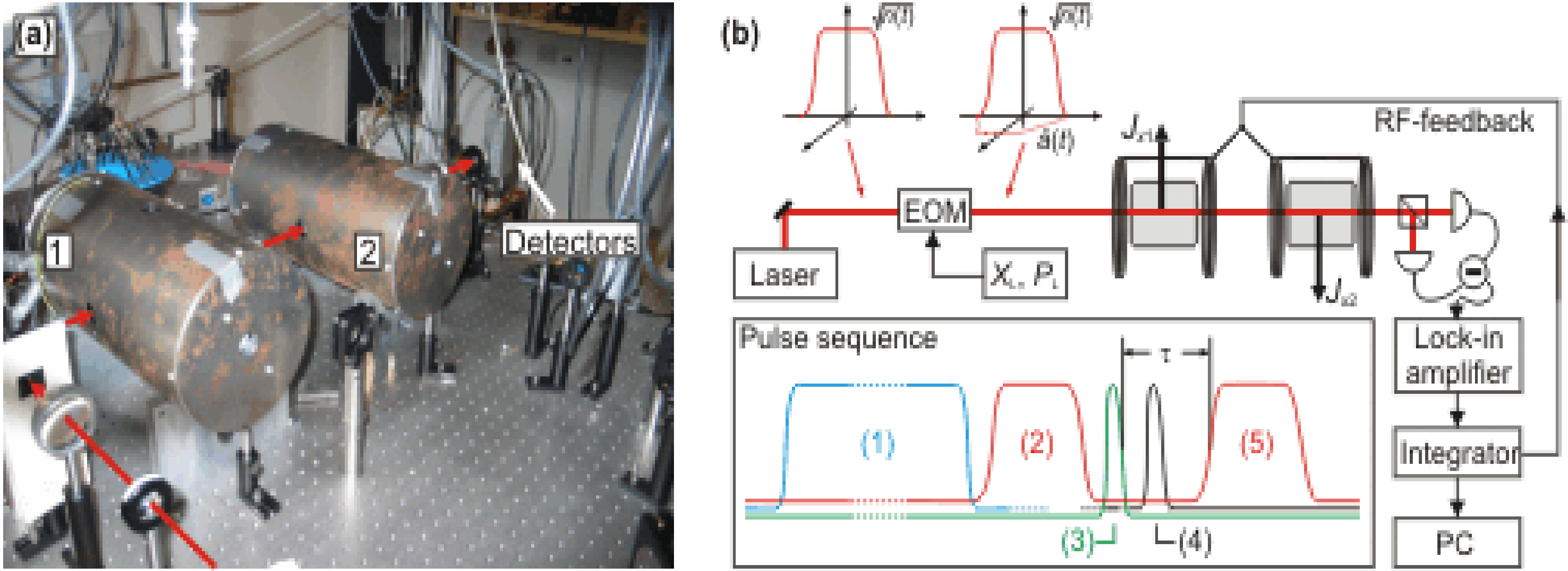
a_x — strong coherent linearly polarized coupling beam

a_y — quantum linearly polarized signal beam

Our main results

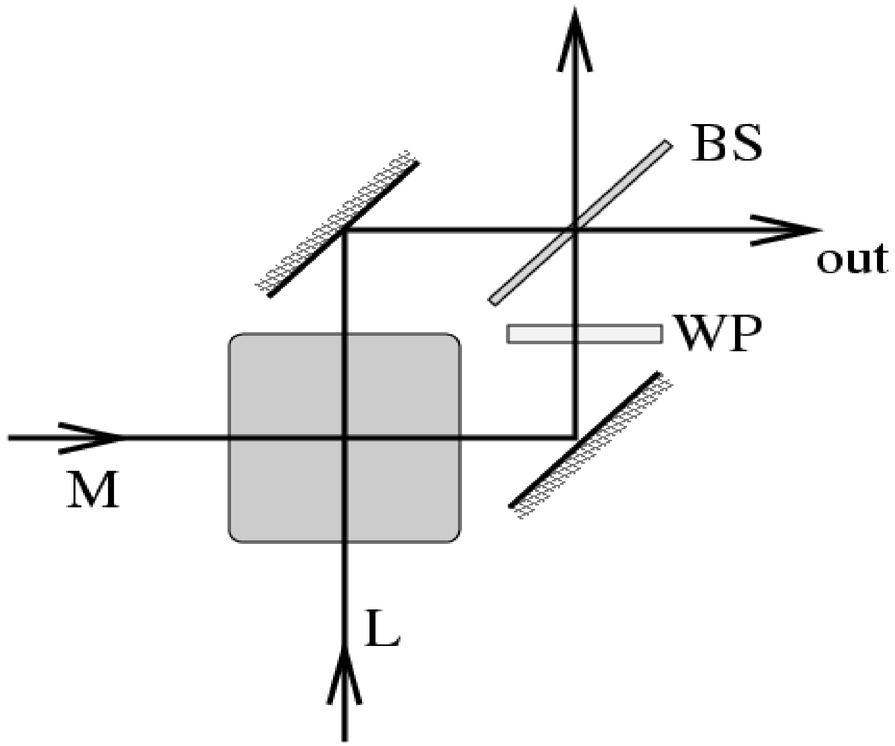
- Quantum gates between atoms and light based on several passages of the light beam through the ensemble
- Protocol for cloning of coherent states into quantum memory
- Quantum memory for light
- Protocols for readout of the quantum memory
- Purification and concentration of coherent states into quantum memory

Quantum memory for light



B. Julsgaard, J. Sherson, J.I. Cirac, J. Fiurášek, and E.S. Polzik, *Nature (London)* **432**, 482 (2004).

Readout protocols



- **Two light beams L and M cross the atomic ensemble simultaneously in perpendicular directions**
- The beam L reads the atomic quadrature x_A and the beam M retrieves the quadrature p_A

J. Fiurášek, J. Sherson, T. Opatrny, and E.S. Polzik, *Phys. Rev. A* **73**, 022331 (2006).

IV. Optimal quantum cloning

No-cloning theorem: an unknown quantum state cannot be copied

Transformation $|\psi\rangle \rightarrow |\psi\rangle|\psi\rangle$

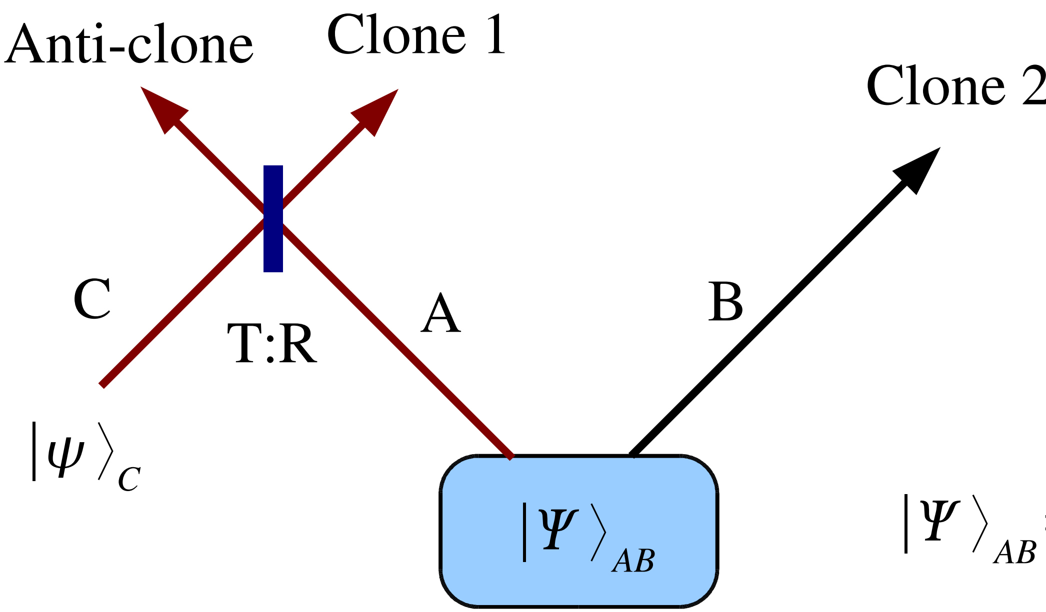
is forbidden by the linearity of quantum mechanics!

- **Optimal quantum cloning machine**
  - best approximation to the forbidden cloning operation
  - can be used as efficient eavesdropping attack on QKD

Our main results

- Optimal cloning machine for coherent states
- Scheme for direct cloning of coherent states into quantum memory
- General method of design of the optimal quantum cloning machine
- Optical scheme for optimal universal asymmetric cloning of polarization states of photons
- Optical scheme for optimal phase-covariant cloning
- Highly asymmetric optimal cloning machines producing several clones of different quality

Partial teleportation as optimal asymmetric cloning



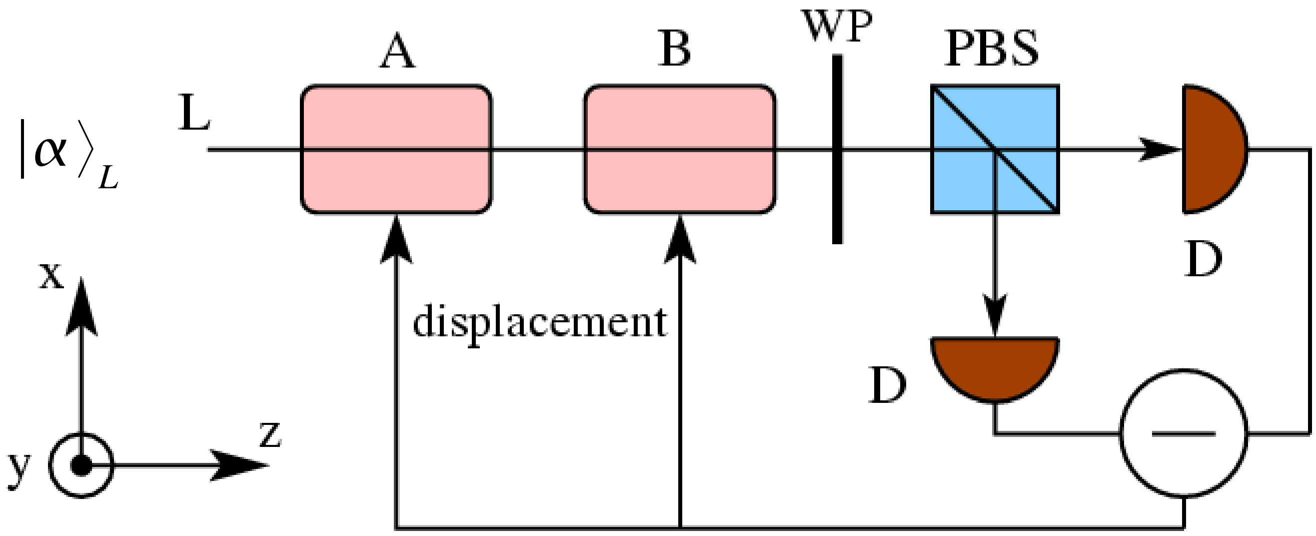
$$|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B)$$

Trade-off between the fidelities of the clones controlled by the splitting ratio T

R. Filip, *Phys. Rev. A* **69**, 052301 (2004).

Z. Zhao, A.-N. Zhang, X.-Q. Zhou, Y.-A. Chen, C.-Y. Lu, A. Karlsson, and J.-W. Pan, *Phys. Rev. Lett.* **95**, 030502 (2005).

Cloning of coherent states into atomic quantum memory

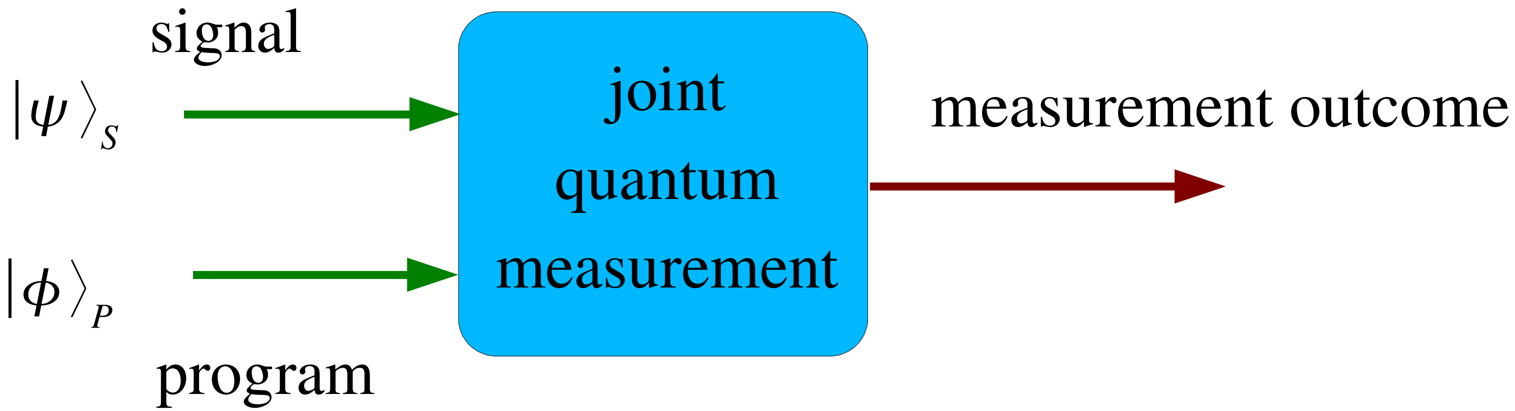


The two clones are stored in the atomic memory units A and B.

J. Fiurášek, N.J. Cerf, and E.S. Polzik, *Phys. Rev. Lett.* **93**, 180501 (2004).

V. Programmable quantum measurement devices

Quantum measurement controlled by quantum ”software”



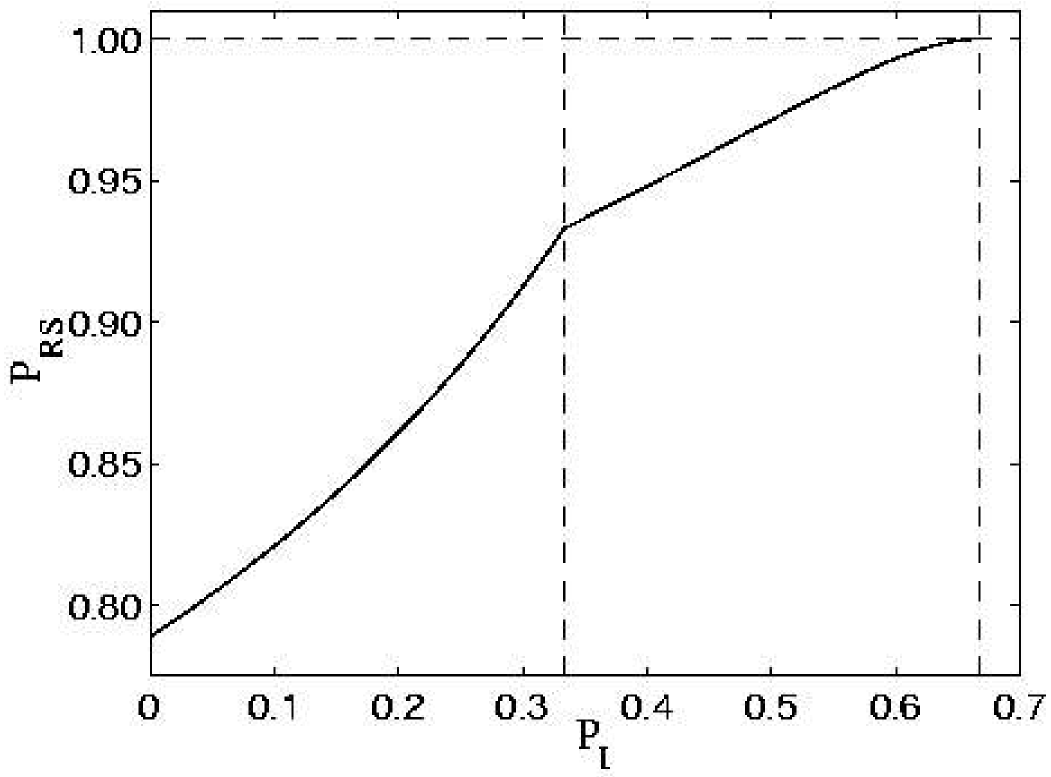
Effective measurement on the signal state is controlled by the quantum state of the program register.

Our main results

- **Optimal quantum multimeters that can approximately accomplish any von Neumann measurement on a single qubit**
  - **program I:** N copies of one basis state $|\psi\rangle^{\otimes N}$
  - **program ii:** a single copy of both basis states $|\psi\rangle|\psi_{\perp}\rangle$
- **Programmable probabilistic quantum measurement devices**
- **Programmable quantum discriminators – the states to be distinguished are specified by the state of program register**
- **Experimental implementation of these devices**

Performance of quantum multimeter for program $|\psi\rangle|\psi_\perp\rangle$

probability of correct measurement results for conclusive outcomes

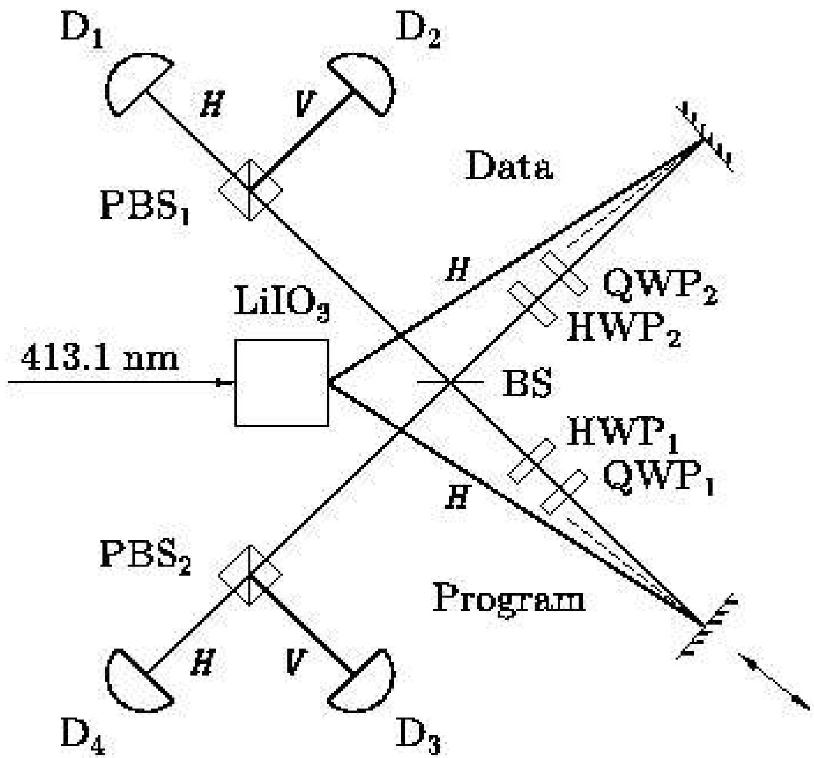


probability of inconclusive measurement outcomes

Due to the finite size of the program register, the measurements can be programmed only approximately

J. Fiurášek and M. Dušek, *Phys. Rev. A* **69**, 032302 (2004).

Experimental implementation



Qubits represented by polarization states of single photons

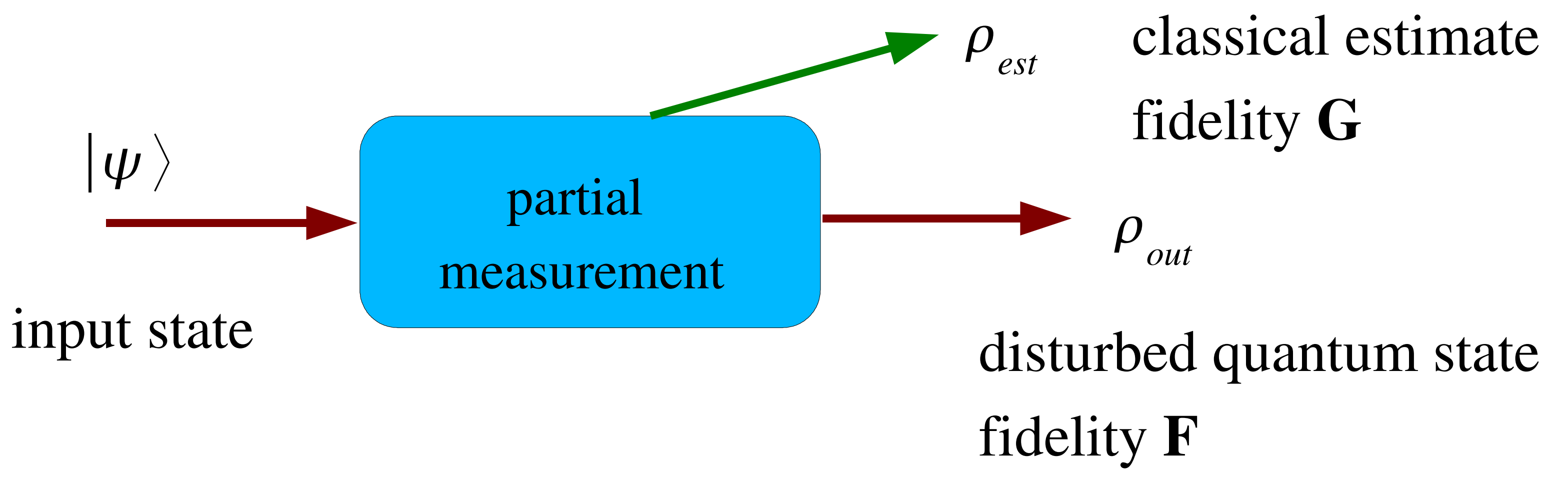
The scheme is based on the Hong-Ou-Mandel interference effect

J. Soubusta, A. Černoch, J. Fiurášek and M .Dušek, *Phys. Rev. A* **69**, 052321 (2004).

VI. Optimal partial measurement of a quantum state

- Quantum state cannot be perfectly determined from measurement on a single copy
- Any measurement disturbs the quantum state that is being measured

Minimum disturbance measurements – yield maximum information on the state for a given amount of disturbance

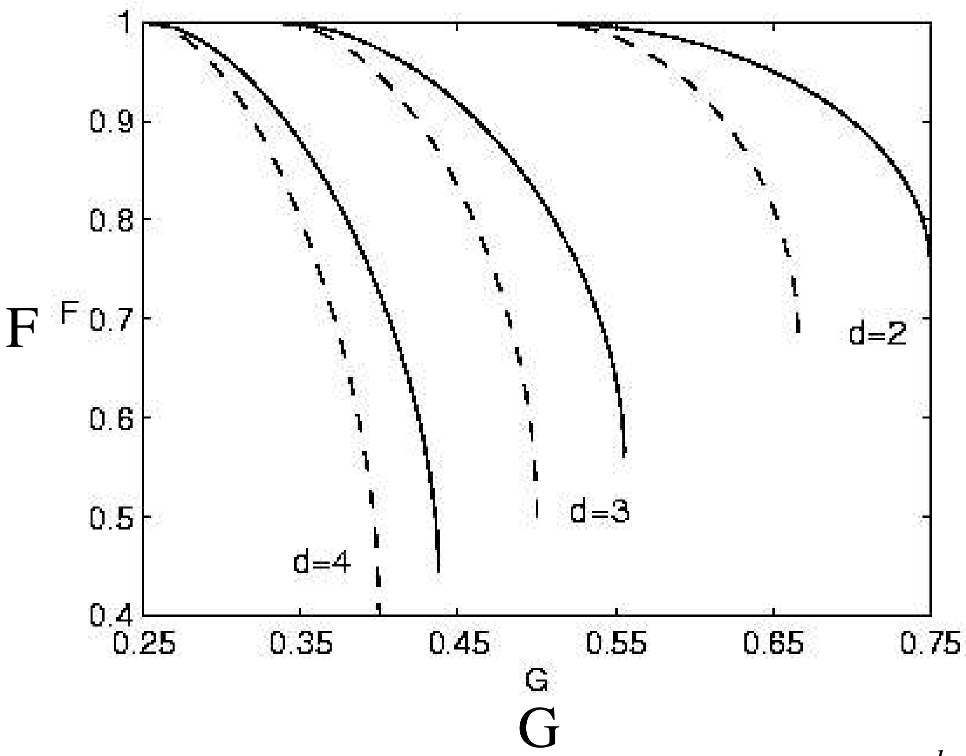


Fidelity – quantifies similarity of two quantum states $F=\langle\psi|\rho|\psi\rangle$

Our main results

- Optimal minimum disturbance measurements for phase-covariant qudits
- General theory of optimal partial estimation of quantum states – formulation of the problem as a semidefinite program
- Minimum disturbance measurements for coherent states
- Scheme for experimental implementation of the partial measurement of the polarization states of photons
- Optimal partial discrimination of quantum states

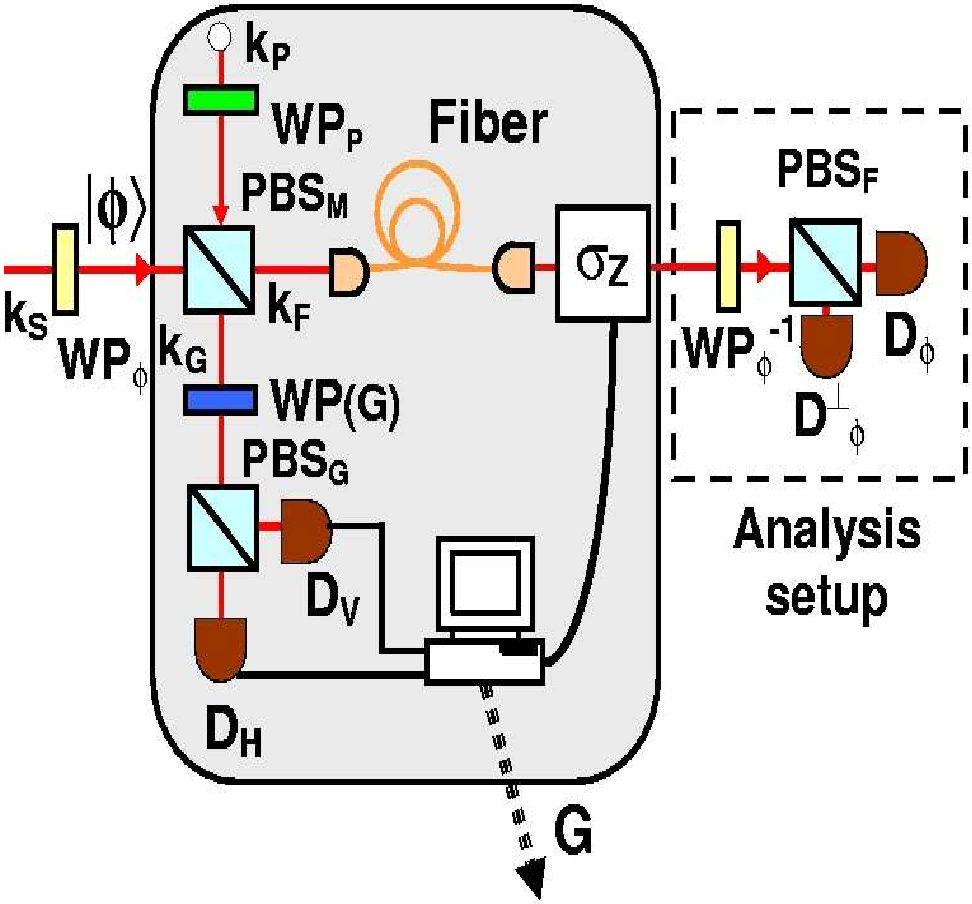
Optimal fidelity trade-offs

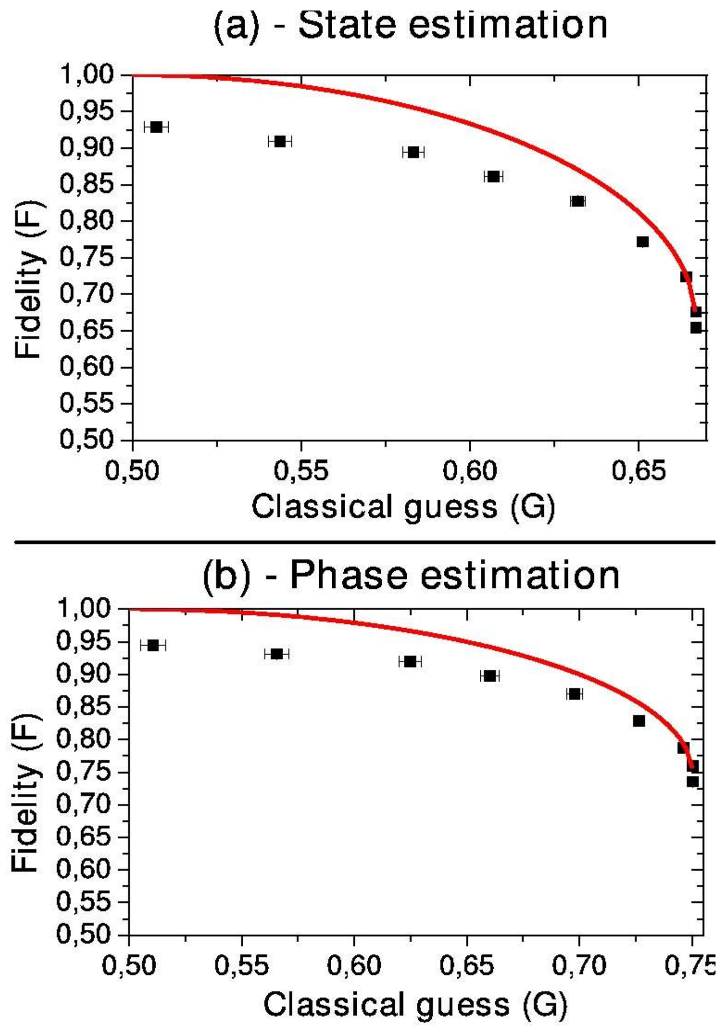


- **Solid lines** – phase-covariant qudits $|\psi\rangle = \frac{1}{\sqrt{d}} \sum_{j=0}^{d-1} e^{i\phi_j} |j\rangle$
- **Dashed lines** – arbitrary qudits (universal partial estimation)

L. Mišta, J. Fiurášek, and R. Filip, *Phys. Rev. A* **72**, 012311 (2005).

Experimental implementation – collaboration with Roma





F. Sciarrino, M. Ricci, F. De Martini, R. Filip, L. Mišta Jr., *Phys. Rev. Lett.* **96**, 020408 (2006).

THE END

Thanks for your attention !