PROJECT PERIODIC REPORT

Grant Agreement number: 212008

Project acronym: COMPAS

Project title: Computing with Mesoscopic Photonic and Atomic State

Funding Scheme: CP-FP-INFSO

Date of latest version of Annex I against which the assessment will be made: 14th Feb. 2008

Periodic report: 1st ■ 2nd □ 3rd □

Period covered: from 1st April 2008 to 31st March 2009

Name, title and organisation of the scientific representative of the project's coordinator:

Prof. Nicolas J. Cerf
Centre for Quantum Information and Communication (QuIC)
Université libre de Bruxelles (ULB)
Brussels, Belgium

Tel: +32 2 650 28 58

Fax: +32 2 650 29 41

E-mail: ncerf@ulb.ac.be

Project website address: http://optics.upol.cz/compas/

Declaration by the scientific representative of the project coordinator

I, as scientific representative of the coordinator this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate):
  - ■ has fully achieved its objectives and technical goals for the period;
  - ☐ has achieved most of its objectives and technical goals for the period with relatively minor deviations;
  - ☐ has failed to achieve critical objectives and/or is not at all on schedule.
- The public website is up to date, if applicable.
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 6) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 5 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: .....Nicolas J. Cerf......................................

Date: ....29..../ .May....../ .2009.........

Signature of scientific representative of the Coordinator: ....

Table of contents

1. Publishable summary

Today's information society is more than ever relying on the secure transfer of sensitive information over public communication networks such as the Internet. In 1994, Peter Shor, from Bell labs, invented a quantum algorithm for the factoring of large numbers, which is exponentially faster than any classical algorithm. If a quantum computer capable of running Shor's algorithm can be built, it would threaten the security of Internet communications because this algorithm could then be used to decipher messages encrypted using widespread public-key cryptosystems such as RSA (Rivest-Shamir-Adleman). Remarkably, in addition to posing this potential threat, quantum physics also provides a revolutionary solution to the problem of secret communication in the form of quantum cryptography. This technique offers the possibility for unconditionally secure communication, whose security is guaranteed by the laws of quantum physics instead of unproven hypotheses on the computational hardness of certain mathematical tasks such as factoring. These seminal discoveries have stimulated, over the last decade, the dramatic development of quantum information science – a young interdisciplinary field aiming at exploring the many novel opportunities offered by quantum physics for processing information. It is nowadays widely recognized that quantum information technologies have the potential to revolutionize the way we compute and communicate.

In the recent years, so-called continuous variables (CV) have emerged as a viable and extremely promising alternative to the traditional quantum bit-based approaches to quantum information processing. Encoding CV information onto mesoscopic carriers, such as the quadrature components of light modes or the collective spin degrees of freedom of atoms, has proven to offer several distinct advantages, making CV a tool of major importance for the development of future informational and computational systems. Several experimental breakthroughs have been achieved that support this promise, for example, the deterministic generation of entangled or squeezed states in optical parametric amplifiers making it possible to perform unconditional quantum teleportation, the high-rate quantum distribution of secret keys using off-the-shelve telecom components, or the highly efficient coupling of light with atoms, allowing the demonstration of a quantum memory for light as well as of inter-species quantum teleportation.

The toolbox of operations that are available for the manipulation of mesoscopic CV states has even been recently extended with conditional photon subtraction, a process which enables the generation of non-classical CV states with negative Wigner functions. This has opened access to the realm of non-Gaussian operations, which are essential to several critical applications such as CV entanglement distillation or CV quantum computing. In view of these recent spectacular achievements, all conditions appear to be met today for the success of a focused research project that explores the various opportunities offered by this CV toolbox to reach concrete informational and computational goals.

COMPAS is a Specific Targeted Research or Innovation Project (STREP) that aims at developing exploratory research on mesoscopic continuous-variable quantum information systems, both on the theoretical and experimental sides, with the ambitious ultimate objective of designing the first small-scale quantum processor using this CV paradigm. In an interplay between theory and experimental research, the consortium investigates the hitherto essentially unexplored potential of CV quantum computing and addresses the necessary steps on the way to mesoscopic CV processors. A particular – high pay-off – application that is targeted is the CV quantum repeater, that is, the small processor that is expected to be found in the nodes of future quantum communication networks. Other main challenges addressed in COMPAS also include the development of CV entanglement distillation, CV quantum computing models, and CV quantum error correction procedures. Harnessing non-Gaussian quantum states is an absolute prerequisite in order to reach these goals, so that the recent proof-of-concept demonstration of non-Gaussian operations achieved by three teams in the world (two of them belonging to the present consortium), warrants the viability and timeliness of the present project. COMPAS will demonstrate the engineering of non-Gaussian operations on photonic and atomic states exploiting the measurement-induced or actual nonlinearities between light and atoms, or CV quantum computing with cat states or cluster states, and will build on these successes in order to develop mesoscopic CV processors. This should initiate a major step in the future of quantum technologies.

As illustrated in the following table, the project consortium is composed of six theoretical groups (ULB, MPG, ICFO, UP, USTAN, POTSDAM) and four – effectively five – experimental groups (CNRS, NBI, DTU, FAU), each having a leading expertise in quantum optics and quantum information theory. It comprises scientists who have been largely involved in the recent developments in continuous-variable quantum information processing. This strong complementarity will ensure that the theoretical ideas developed in the course of the project will be demonstrated by the experimental groups in a close collaboration. As a matter of fact, although the 3 scientific workpackages (WP1-2-3) are all led by experimentalists, virtually all main research tasks within COMPAS will be carried out jointly by theorists and experimentalists. This strong interplay between theory and experiments strengthens the need for a supra-national collaborative scale in order to reach the ultimate objectives of the project.

Part. Nr	**Participant name**	**Participant short name**	**Country**	**Team leader**	**Nature of work**
1 (CO)	Université Libre de Bruxelles	ULB	BE	Nicolas J. Cerf (Coordinator)	THE
2	Max-Planck-Gesellschaft	MPG	DE	J. Ignacio Cirac	THE
3	Institut de Ciencies Fotoniques	ICFO	ES	Antonio Acin	THE
4	Univerzita Palackého v Olomouci	UP	CZ	Jaromir Fiurasek (Deputy coordinator)	THE
5	University of St. Andrews	USTAN	UK	Natalia Korolkova	THE
6	Universitaet Potsdam	POTSDAM	DE	Jens Eisert	THE
7	Centre National de la Recherche Scientifique	CNRS/IO CNRS/ENS	FR	Philippe Grangier (WP1 leader) Elisabeth Giacobino	EXP EXP
8	Kobenhavns Universitet (Niels Bohr Institute)	UCPH (NBI)	DK	Eugene S. Polzik (WP2 leader)	EXP
9	Danmarks Tekniske Universitet	DTU	DK	Ulrik L. Andersen (WP3 leader)	EXP
10	Friedrich-Alexander-Universität Erlangen-Nürnberg	FAU	DE	Gerd Leuchs	EXP

List of participants in COMPAS, including the names of team leaders
and the nature of the work (THEory or EXPeriments).

Finally, the duration of the project is 36 months, which is appropriate in order to assess the general viability of CV quantum computational systems. All the details on the objectives and progresses of the project can be found in the website of COMPAS, which is available at:

http://optics.upol.cz/compas/

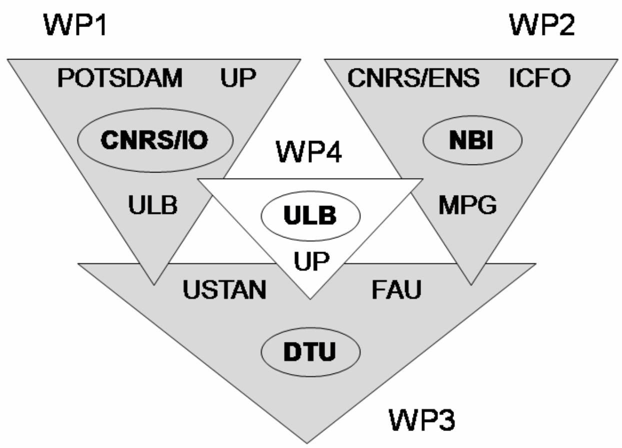
It is anticipated that the COMPAS project will have a strong impact on the future of ICT-related technologies and further strengthen the pan-European cooperation in a research area where Europe has started to establish itself at the leading edge.

2. Project objectives for the period

There is a very important and well established research effort worldwide in an attempt to realize quantum computers able to solve hard computational problems. Several technologies are envisaged, but the common philosophy is generally to seek for ways to control a register consisting of quantum bits. This can be viewed as a *top-down* approach in the sense that the informational and/or computational tasks that could be achieved are already identified, at least in part, while the core problem lies in the physical implementation of the quantum computer. The planned research within the COMPAS project breaks this paradigm: it is oriented towards the specific goal of investigating and designing small-scale continuous-variable (CV) quantum processors, where several photonic and/or atomic modes would interact in a controlled manner. Such small processors could, for instance, form the nodes of advanced quantum communication networks, or achieve quantum error correction. In this respect, the current project rather pursues a *bottom-up* approach, starting from a CV toolbox that has already shown a remarkable success in the laboratory, and then building on it to achieve a probably more modest but also more realistic goal.

More specifically, the concrete objectives of COMPAS are to experimentally demonstrate several computational tasks that represent fundamental steps on the way to mesoscopic CV processors. For instance, it is indispensable to engineer highly non-Gaussian states of light and atoms (with negative Wigner functions) in order to achieve most relevant CV computational processes, so that this task will be a central objective of the project. In parallel, specific models for CV quantum computing will be investigated (first theoretically, then experimentally), such as one-way computing based on CV cluster states. The major role of non-Gaussian quantum states in this context also motivates the investigation of nonlinearities in atomic media (atomic vapors or cold atoms) in order to use them as quantum interfaces for CV quantum information or as a means to effect novel photonic quantum gates. Another critical research topic concerns measurement-induced nonlinearities as an alternative method to realize informational tasks such as the distillation of non-Gaussian entangled states, a crucial step towards CV quantum repeaters. Finally, “cat-states” computing , i.e., quantum computing based on mesoscopic states, is another theme which very naturally arises on the way to CV computing, so that the generation and “breeding” of cat states will be of major importance in this project. These various topics will be studied by theoretical teams of the consortium, and, whenever possible, addressed simultaneously in unison with experimental teams.

COMPAS is structured into 3 scientific workpackages (WP1-3), which are organized in a “star-shaped” structure and will be carried out by specific subgroups of the consortium (see chart below). In a nutshell, WP1 is centered on the *design of photonic building blocks* while WP2 focuses on the *design of atomic building blocks*, both with the specific perspective of realizing continuous-variable information processing. These two workpackages are rather “component-oriented”, while the third scientific workpackage (WP3) is more “system-oriented”. It should integrate the outcomes of WP1 and WP2 towards the goal of *experimentally demonstrating mesoscopic CV quantum processors or algorithms*. Finally, a last workpackage WP4, led by the coordinator, is devoted to the consortium management.



Organizational structure of COMPAS.
Solely the “leading” and “supporting” partners are shown here (leading partners are circled), while the involvement of “auxiliary” partners is not shown.

WP1 objectives

The “hard core” of this workpackage is primarily devoted to the engineering of mesoscopic quantum states of light, viewed as a central prerequisite to CV quantum processors. This experimental research effort will be supplemented with a main theoretical activity on CV quantum computing, centered on photonic CV information carriers. We will investigate the measurement-induced techniques, where conditioning on single-photon or homodyne detection is used to effect interesting informational operations. We will also explore the prospects of one-way quantum computing with CV cluster states, the simulation of physical systems by CV processors, and even the related foundational issue of the non-locality of CV states (e.g., the classical simulation of CV states with negative Wigner function). This is precisely the point where non-Gaussian states and operations play a central role as it is known that quadratic Hamiltonians (which generate Gaussian states) are insufficient in several applications such as universal computing, entanglement distillation, Bell tests, etc. Thus, a major goal of WP1, on the experimental side, will be the generation of high-purity non-Gaussian mesoscopic states of light with negative Wigner function. This will further lead, in WP3, to the demonstration of quantum gates such as the C-NOT and Hadamard gates, and eventually of cat-state CV computing.

WP2 objectives

This workpackage is concerned with the physical implementation of the quantum gates or operations used in protocols where atomic information carriers need to be manipulated (in addition to photonic ones). This will, almost by definition, involve the nonlinear interaction of light with matter (with a higher than 2^{nd} order in the canonical variables for non-Gaussian operations). We will first exploit the available techniques and interactions, such as de-Gaussification, measurement-induced operations, feedforward, and non-resonant interaction of light with atoms in order to design more complex (non-Gaussian) interactions between several modes, while optimizing the fidelity and success rate of these schemes. On the theory side, the physics of the various sources of nonlinear coupling will be investigated in depth, such as the Faraday effect in dense atomic vapors, the coupling of light to a BEC, the cross-Kerr effect in EIT, and even the giant (photon-photon) nonlinearities of single-photon pulses traveling in optical cavities. On the experimental side, new techniques to realize more efficient and longer-lived quantum atomic memories for light will be developed and tested. The engineering of high-purity non-Gaussian mesoscopic states of atoms with negative Wigner function will be still another major goal, paving the way to the experimental demonstration, in WP3, of CV entanglement purification and, ultimately, of CV quantum repeaters. Alternative quantum network geometries will also be analyzed in this perspective.

WP3 objectives

This workpackage is concerned with the experimental proof-of-principle demonstration of more advanced schemes, parts of the mesoscopic CV quantum processor envisaged in the theoretical tasks of the project. This will require the combination of the experimental procedures developed in WP1-2 into more sophisticated schemes. For example, we intend to demonstrate the generation of multimode entangled states of light and atoms which could be used for teleportation-based implementation of quantum operations as well as the preparation of optical CV cluster states, which could be used in one-way quantum computing. This also includes the theoretical identification of the operations required for computational applications such as entanglement distillation or concentration in the nodes of a CV quantum network. In parallel, the demonstration of CV quantum error correction and CV cat-states quantum computing (using cat states as ancillas and homodyne detection for conditioning) will also be central components of WP3. The interaction between the project partners will be more pronounced in this workpackage since several experimental techniques will need to be transferred from WP1-2. Finally, the ultimate goal of WP3 will be to assess the prospects of mesoscopic CV quantum processors and algorithms.

3. Work progress and achievements during the period

Workpackage 1: Design of photonic components of CV quantum computing

Period covered: from 01/04/08 to 31/03/09
Organisation name of lead contractor for this workpackage: CNRS/IO
Other contractors involved: ULB, FAU, UP, USTAN, POTSDAM

Progress towards objectives of WP1 during year 1 of the project

The most significant experimental progress has been achieved in the areas of the generation of highly nonclassical entangled states of light and the tomography of quantum measurements, resulting in two publications in Nature Physics by COMPAS partners. Partner CNRS/IO successfully experimentally demonstrated a simple approach to generating strongly entangled non-local superpositions of coherent states, using a very lossy quantum channel. Such superpositions should be useful for implementing coherent qubit-rotation gates, and for teleporting these qubits over long distances. The generation scheme may be extended to creating entangled coherent superpositions with arbitrarily large amplitudes. In collaboration with the experimental group of Prof. I.A. Walmsley, partner POTSDAM performed the first full quantum detector tomography that makes no a-priori and possibly unjustified assumptions on the detector device. Such a full detector tomography was done for several photon detecting or counting detectors, exploring ideas of multiplexing. In addition, partner FAU succeeded in generation and direct detection of broadband mesoscopic polarization-squeezed vacuum in a traveling-wave OPA. Furthermore, partner DTU demonstrated the generation of quadrature squeezed surface-plasmons in a gold waveguide and observed spatial correlations of photons of genuine quantum origin that are induced by multiple scattering of squeezed light.

On the theory side, partner POTSDAM made important progress in the characterization of CV entanglement. A complete classification of all Gaussian memoryless channels has been given. The marginal problem that asks whether for given reduced states a pure state can be found which is consistent with the given reductions was solved for Gaussian states. This gives rise to bounds on entropies and entanglement if one can perform local photon counting on a multimode state of light. Partner ULB derived necessary conditions (bounds) on the non-Gaussianity for a state to have a positive Wigner function, in an attempt to extend Hudson’s theorem beyond pure states. Partners ULB and ICFO investigated Bell tests involving homodyne measurements performed on multimode continuous-variable light states and proved that the Mermin-Klyshko inequality can be violated by an amount that grows exponentially with the number of modes. Partner UP investigated implementation of various CV quantum gates using ancillary non-Gaussian quantum states and Gaussian operations and measurements. Partner POTSDAM proposed a systematic framework of quantum computational schemes on the basis of local measurements on certain non-Gaussian states. Such non-Gaussian states emerge formally from a description in terms of so-called matrix product states with infinite physical dimension and finite bond dimension, to make quantum error correction possible, hence overcoming the no-go-theorem for Gaussian quantum error correction established by partners ULB and UP in WP3 (Task 3.2).

<u>Task 1.1</u>: Basic concepts and theoretical tools for CV information processing

Deliverable 1.1: ***Characterization of CV entanglement***

Status: Due month 12; Delivered on time; Unexpected extra progress reported

Partners: ULB, POTSDAM, ICFO, CNRS/IO, DTU, FAU

This task first aims at characterizing and detecting quantum entanglement in multipartite non-Gaussian states. In contrast to the case of Gaussian states, few results exist for non-Gaussian states. In view of the importance of the latter states in this project, one of the goals of the present project is to develop methods to infer (bounds on) the entanglement out of the experimentally available data, requiring fewer data than full quantum state tomography but without making *a priori* assumptions on the state. Another specific objective is the understanding of the minimum "non-Gaussian resources" needed to perform a "useful" computation (which cannot be simulated classically). In particular, the link between the "non-Gaussianity„ and the negativity of the Wigner function deserves to be better elucidated for mixed states. In addition to achieving these goals, several unexpected results have been obtained that are related to CV entanglement and non-locality, and are therefore reported here.

Reported progress towards Deliverable 1.1:
Characterization of CV entangled quantum states and quantum channels.
(Partner POTSDAM)

Partner POTSDAM made progress on the unambiguous characterization of CV entanglement that only makes use of measurement data, but is not based on any assumptions on the states being prepared. Such an analysis gives rise to lower bounds to entanglement measures that do not depend on possibly unjustified a-priori assumptions, tools that can be used to unambiguously certify success in CV entanglement distillation schemes.

A first result is a complete classification of all Gaussian memoryless channels, as they appear in multi-mode communication channels [1]. Second, we consider the marginal problem, i.e., asking whether for given reduced states a pure state can be found which is consistent with the given reductions [2]. We established a general result on that for Gaussian states, mirroring the celebrated result on the qubit solution by Klyachko. Formally, the solution can be viewed as a symplectic variant of the Sing-Thompson theorem. Practically speaking, it gives rise to bounds on entropies and entanglement if one can do local photon counting to a multimode state of light: One can immediately ask for maximum degrees of entanglement, if only such measurements without a phase reference are available.

Partner POTSDAM also has authored a perspectives article in the Nature magazine on the flexible preparation of multi-mode entangled light. We also made use of the opportunity to discuss the impact of event-ready continuous-variable preparations of entangled states of light [3]. We have also done a significant amount of original research on CV states of atoms in optical lattices [4-6], which is relevant for the characterization of CV entanglement. This includes work on entanglement dynamics, apparent local relaxation, and non-equilibrium dynamics in such CV systems. Atomic

CV systems in this sense offer new perspectives in the study of non-Gaussian CV systems of many modes.

Publications:

[1] F. Caruso, J. Eisert, V. Giovannetti, and A.S. Holevo, *Multi-mode Gaussian bosonic channels*, New J. Phys. **10**, 083030 (2008).

[2] J. Eisert, T. Tyc, T. Rudolph, and B. Sanders, *Gaussian quantum marginal problem*, Communications in Mathematical Physics, **280**, 263 (2008).

[3] M. Aspelmeyer and J. Eisert, *Entangled families,* in News and Views, Nature **455**, 180 (2008).

[4] M. Cramer, A. Flesch, I.P. McCulloch, U. Schollwoeck, and J. Eisert, *Exploring local quantum many-body relaxation by atoms in optical superlattices*, Phys. Rev. Lett. **101**, 063001 (2008).

[5] A. Flesch, M. Cramer, I.P. McCulloch, U. Schollwoeck, and J. Eisert, *Probing the local relaxation of cold atoms in optical superlattices*, Phys. Rev. A **78**, 033608 (2008).

[6] M. Cramer, A. Serafini, and J. Eisert, *Locality of dynamics in general harmonic systems*, in Quantum Information and Many-Body systems, Pisa, Edizioni della Normale (2008).

Reported progress towards Deliverable 1.1:
Relation between non-Gaussian CV mixed states and non-positive Wigner functions
(Partner ULB)

One of the central objectives of COMPAS is to gain a better understanding of the non-Gaussian states and operations that are necessary for CV quantum information processing. As already explained, non-Gaussian states are known to be indispensable in, e.g., CV entanglement purification, CV quantum computing, and for tests of nonlocality based on homodyne detection applied to CV quantum states. Actually, non-Gaussian states are crucial because they have the peculiar property that (for pure states) their Wigner function attains negative values in some regions of phase space. This is the content of the famous theorem due to Hudson R.L. Hudson {1} and later generalized to multi-mode quantum systems by F. Soto et al.{2}: "Among pure states, the only states which have non-negative Wigner functions are Gaussian states".

It is generally assumed that it is the negativity of the Wigner function which is relevant for CV quantum information tasks, more than the non-Gaussian character of the state. Therefore, a question that arises naturally is whether Hudson's theorem can be extended to mixed states, among which not only Gaussian states may possess a positive Wigner function. It is of course crucial to treat the case of mixed states since these are the states actually available in the laboratory (pure states correspond to an ideal case, hardly realizable in practice). A logical extension of the theorem would start with a complete characterization of the convex set of states with positive Wigner function. Although this question has been approached R. Werner and collaborators by using the notion of Wigner spectrum {3}, a simple and operational extension of Hudson's theorem has not yet been achieved due to the mathematical complications which emerge when dealing with states with positive Wigner functions.

Motivated by the increasing interest for non-Gaussian states in continuous-variable quantum information theory and the need for a better understanding of the de-Gaussification procedures for mixed states, partner ULB has attempted to explore the set of states with positive Wigner functions using Gaussian states as a reference (more precisely, considering the subset of non-Gaussian states with positive Wigner function that have the same covariance matrix as a reference Gaussian state). Partner ULB has obtained a partial solution to this problem, by analytically deriving necessary conditions (bounds) on the non-Gaussianity for a state to have a positive Wigner function. This set of conditions bounds a region in a three-dimensional space with coordinates being the purity of the state, the purity of the corresponding Gaussian state, and the non-Gaussianity. As intuitively expected, the maximum degree of non-Gaussianity increases with a decrease of the purity of the Gaussian reference state. Furthermore, these derived conditions permit, in principle, the existence of non-Gaussian states having a lower purity than the corresponding Gaussian states with the same covariance matrix. Several physical examples of such states that are ``more random" than their Gaussian counterpart have been exhibited. This is a very counterintuive feature given that Gaussian states are well known to be extremal in the sense that they maximize the von Neumann entropy for a fixed covariance matrix.

References:

{1} R.L. Hudson, Rep. Math. Phys. **6**, 249 (1974).
{2} F. Soto and P. Claverie, J. Math. Phys. **24**, 97 (1983).
{3} T. Bröckner and R.F. Werner, J. Math. Phys. **36**, 62 (1995).

Publications:

A. Mandilara, E. Karpov, and N. J. Cerf, *Extending Hudson's theorem to mixed quantum states*, accepted for publication in Phys. Rev. A. (see also arXiv:0808.2501 [quant-ph]).

Conference presentations:

A. Mandilara, E. Karpov, J. Niset, and N. J. Cerf, *Bounds on the non-Gaussianity of mixed quantum states with positive Wigner functions*, Solvay Workshop "Bits, Quanta, and Complex Systems: modern approaches to photonic information processing", April 30 - May 05, 2008, Brussels, Belgium. [POSTER]

N. J. Cerf, *On Hudson's Theorem: from pure to mixed states*, Symposium to celebrate the achievements of Anthony Sudbery on the occasion of his 65th birthday, September 29-30, 2008, University of York, UK. [INVITED TALK]

N. J. Cerf, *On Hudson's Theorem: from pure to mixed states*, 2008 xQIT Conference on Difficult Problems in Quantum Information Theory, Massachusetts Institute of Technology, Boston, USA, November 19-20, 2008. [INVITED TALK]

A. Mandilara, E. Karpov, and N. J. Cerf, Towards an extension of Hudson’s theorem to mixed quantum states, 16th Central European Workshop on Quantum Optics (CEWQO 2009), May 23-27, 2009, Turku, Finland. [CONTRIBUTED TALK]

Reported progress towards Deliverable 1.1: **(Unexpected extra progress)**
Test of multimode CV quantum nonlocality
(Partners ICFO and ULB)

The incompatibility of quantum mechanics with local realistic models is inarguably one of its most counterintuitive aspects, marking a fundamental departure from the classical picture of physical systems. There is a large variety of quantum systems for which a test of local realism may be envisaged. However, the quest for a *loophole-free* Bell test has recently focused the research towards experiments involving propagating light modes measured with homodyne detectors. The advantage of this continuous-variable approach is twofold. First, light modes can be easily sent to spacelike separated detectors, suffering only a tolerable degree of decoherence, thus circumventing the locality loophole. Second, the current technology of homodyne detectors achieves a degree of detection efficiency high enough to potentially close the detection-efficiency loophole.

On the other hand, such an continuous-variable approach also involves drawbacks whose resolution is still challenging. The main issue comes from the fact that the results of homodyne measurements can be described by means of the Wigner function. Thus, in order to avoid a local hidden variable description of the measured correlations, one should necessarily perform the test with a state endowed with a non-positive Wigner function (otherwise, the Wigner function is a genuine probability distribution, which provides an explicit local realistic model of the data). This is one of the motivations in COMPAS for generating and harnessing non-Gaussian states of traveling light with a non-positive Wigner function.

Among the proposals of CV Bell tests with homodyne detection, those nearer to an experimental realization only give a small violation of Bell inequalities {1,2,3}, whereas higher violations involve states whose actual generation seems hardly practicable {4}. In this context, the search for Bell tests involving feasible resources and giving, at the same time, violations that are high enough to be robust against experimental noise is very desirable. Partners ULB and ICFO have purused this research direction by investigating Bell tests involving homodyne measurements performed on multimode continuous-variable light states. By binning the measurement outcomes in an appropriate way, it was proven that the Mermin-Klyshko inequality can be violated by an amount that grows exponentially with the number of modes. Furthermore, the maximum violation allowed by quantum mechanics was shown to be attainable for any number of modes, albeit requiring a quantum state whose generation is hardly practicable. Interestingly, this exponential increase of the violation holds true even for simpler states, such as multipartite GHZ states. The resulting benefit of using more modes was also shown to be significant in practical multipartite Bell tests by analyzing the increase of the robustness to noise with the number of modes. An explicit example of a three-mode state was exhibited, which results in a significant violation of the Mermin-Klyshko inequality (around 10%) with homodyne measurements. A scheme for the generation of this latter state is shown in the figure below. In view of the high efficiency achievable with homodyne detection, these results may open a promising way towards feasible loophole-free CV Bell tests that are robust to experimental imperfections.

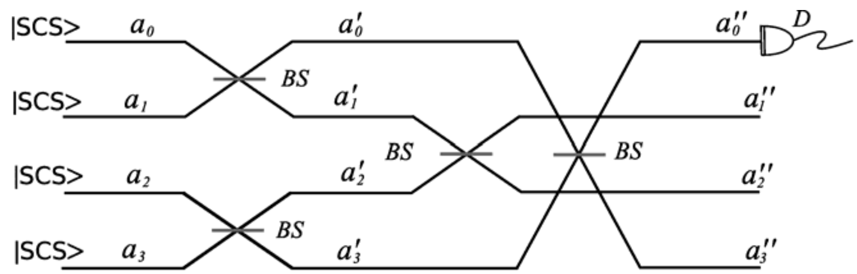


Figure: Scheme for the generation of a three-mode state leading to a significant Bell's inequality violation with homodyne measurements. The scheme starts with four states which are the superposition of coherent states, followed by a sequence of beam-splitters and conditioned on the result of a homodyne measurement performed on one of the modes.

References:

{1} R. García-Patrón, J. Fiurasek, N. J. Cerf, J. Wenger, R. Tualle-Brouri, and P. Grangier, Phys. Rev. Lett. **93**, 130409 (2004)
{2} R. García-Patrón, J. Fiurasek, and N. J. Cerf, Phys. Rev. A **71**, 022105 (2005).
{3} H. Nha and H. J. Carmichael, Phys. Rev. Lett. **93**, 020401 (2004).
{4} J. Wenger, M. Hafezi, F. Grosshans, R. Tualle-Brouri, and P. Grangier, Phys. Rev. A **67**, 012105 (2003).

Publications:

A. Acín, N.J. Cerf, A. Ferraro, and J. Niset, *Tests of multimode quantum non-locality with homodyne measurements*, Phys. Rev. A **79**, 012112 (2009).

Reported progress towards Deliverable 1.1: (Unexpected extra progress)
Generation and Direct Detection of Broadband Mesoscopic Polarization-Squeezed Vacuum (Partner FAU)

Partner FAU investigated the production of squeezed light in a traveling-wave OPA, which differs from fiber squeezing systems in the amount of excess noise and number of photons involved. The advantages of producing squeezed light without a cavity are that, first, there are no additional losses and, second, the output radiation is broadband both in frequency and transverse wavevector (angle of emission). At the same time, observation of squeezing via the direct detection of broadband squeezed vacuum is based on certain experimental requirements such as, for instance, multimode detection.

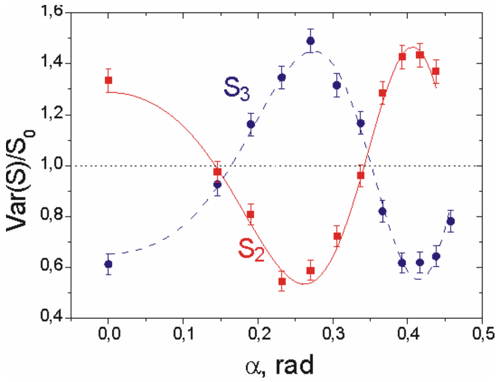


Figure: *Variances of the S_2 and S_3 Stokes observables measured versus the tilt of quartz plates.*

Using a traveling-wave OPA with two orthogonally oriented type-I BBO crystals, cut for collinear frequency-degenerate phase matching and pumped by picosecond pulses, we have generated vertically and horizontally polarized squeezed vacuum states within a broad frequency-angular range. Their superposition formed a state with polarization squeezing: depending on the phase between the squeezed vacuums, fluctuations in one or another Stokes observable were suppressed below the shot-noise limit. Due to the large number of photon pairs produced, no local oscillator was required, and 3dB squeezing was observed by means of direct detection. The figure above shows variances of the S_2 and S_3 Stokes observables measured versus the tilt of quartz plates introducing the phase shift between the squeezed vacuums in orthogonal polarizations.

Publications:

T. Iskhakov, M. V. Chekhova, and G. Leuchs, *Generation and direct detection of broadband mesoscopic polarization-squeezed vacuum*, Phys. Rev. Lett. **102**, 183602 (2009).

M. Avenhaus, M. V. Chekhova, L. A. Krivitsky, G. Leuchs, and C. Silberhorn, *Experimental verification of high spectral entanglement for pulsed waveguided spontaneous parametric down-conversion*, Phys. Rev. A 79, 043836 (2009).

Conference presentations:

T.Sh.Iskhakov, *Two-mode squeezing in parametric down-conversion*, XII International Conference on Quantum Optics and Quantum Information, 20-23 September 2008. [POSTER]

M.V.Chekhova, *Photon correlations and two-mode squeezing in a travelingwave OPA*, XII International Conference on Quantum Optics and Quantum Information, 20-23 September 2008 [INVITED TALK].

M.V.Chekhova, *Polarisation tomography of macro- and mesoscopic quantum states of light*, Workshop Quantum Estimation: Theory and Practice. August 25 - 30, 2008, Perimeter Institute, Waterloo, Canada. [TALK]

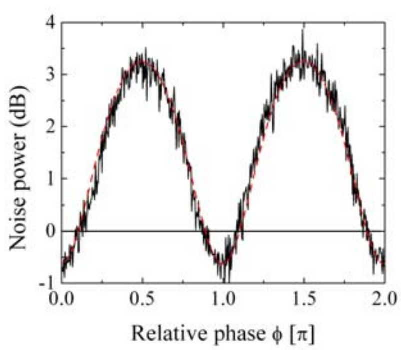
Reported progress towards Deliverable 1.1: (Unexpected extra progress)
Demonstration of Quadrature Squeezed Surface-Plasmons in a Gold Waveguide
(Partner DTU)

The squeezed light resources that are used to implement CV quantum information protocols have been also employed to investigate the propagation of squeezed state plasmons in a metallic waveguide and to explore the spatial structure of squeezed light scattered off a multiple scattering medium. Moreover, we have operated an optical parametric oscillator in a two-mode configuration, thereby producing two squeezed states in higher order spatial modes and as a consequence CV entanglement between the two first-order Laguerre-Gaussian modes.

The efficient propagation of quantum states on a metallic wire might play an important role in future quantum technologies as it allows for very strong light confinement, and thus leading to potential strong interaction with a medium as well as miniaturization. Multiple scattering of quantum states of light and multimode optical parametric oscillators have the potentials to increase the information capacity of quantum communication protocols and is also likely to play an interesting role in future quantum computer technologies.

Partner DTU carried out an experiment demonstrating the generation of non-classical SPPs by exciting them with a squeezed optical light field generated using a bow-tie shaped optical parametric oscillator operating below threshold. Free space optics and end-fire coupling are used for the excitation of long-range SPPs (LR-SPPs) on gold stripes embedded in lossless transparent polymer BCB. The gold stripes have a length, width, and height of 2mm, 1μm, and 14nm, respectively. At maximum, we measure a total transmission of 33.2±0.5% through the sample. The squeezed vacuum input mode and the LR-SPP output mode are characterized using an optical homodyne detection system. We employ the maximum likelihood method to reconstruct the density matrices of the squeezed vacuum input state and the LR-SPP output state. The noise power of the LR-SPP output state as a function of relative phase is presented in the figure (a). We simulate the impact of the LR-SPP mode by applying a beam-splitter operation on the squeezed vacuum input mode. The overlap between the calculated output mode and the LR-SPP mode is evaluated by calculating the Fidelity between the two states, which peaks for a transmission of η=33%, as shown in the figure (b). This result is in very good agreement with the transmission measured classically and proves the validity of the beam-splitter model in the limit of low photon number excitation.

(a)



(b)

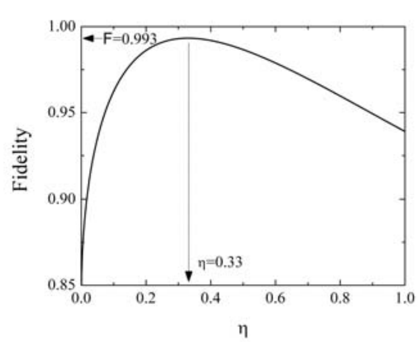


Figure: *(a) Noise variance of the LR-SPP output state calculated from the time resolved data (black solid line) and from the reconstructed LR-SPP states density matrix (red dashed line). (b) Calculated overlap between the squeezed vacuum input state and the LR-SPP output state for various transmissions η through a beam splitter.*

In conclusion, partner DTU demonstrated the excitation of non-classical LR-SPPs and verified, that the transmission of LR-SPP modes in a metallic waveguide can be described by a beam-splitter operation.

Publications

Huck, S. Smolka, P. Lodahl, A. S. Sørensen, A. Boltasseva, and U. L. Andersen, '*Demonstration of Quadrature Squeezed Surface-Plasmons in a Gold Waveguide*', submitted for publication (preprint arXiv:0901.3969v1).

Conference presentations

A. Huck, S. Smolka, P. Lodahl, A. Boltasseva, J. Janousek, and U. L. Andersen, '*Generation of Non-Classical Surface-Plasmon-Polaritons*', oral presentation at the meeting of the Danish Optical Society (DOPS) 2008 Nyborg/Denmark

A. Huck, S. Smolka, P. Lodahl, A. Boltasseva, J. Janousek, and U. L. Andersen, '*Generation of Non-Classical Surface-Plasmon-Polaritons*', oral presentation at the conference on 'Plasmonics and Metamaterials' (META) 2008, Rochester/USA

A. Huck, U. L. Andersen, S. Smolka, A. Boltasseva, and P. Lodahl, '*Excitation and Characterization of Non-Classical Surface Plasmon Polaritons*', poster presentation at the European Topical Meeting on Nanophotonics and Metamaterials 2009 Seefeld/Austria

A. Huck, S. Smolka, L. Krivitsky, P. Lodahl, A. S. Sørensen, A. Boltasseva, and U. L. Andersen, '*Demonstration of Quadrature Squeezed Surface-Plasmons in a Gold Waveguide*', oral presentation at the Conference on Lasers and Electro-Optics - Europe (CLEO) 2009 Munich/Germany

---

Reported progress towards Deliverable 1.1: (Unexpected extra progress)
Experimental Demonstration of Spatial Quantum Correlations in Multiple Scattering Media
(Partner DTU)

Partner DTU demonstrated the experimental realization of spatial correlations of photons of genuine quantum origin that are induced by multiple scattering of squeezed light. As a non-classical source, we used vacuum squeezed light generated with a periodically poled KTiOPO4 crystal. The vacuum squeezed state is overlapped with a bright displacement beam on a beam splitter. Depending on the phase difference between the vacuum squeezed state and the displacement beam we are able to tune the photon fluctuations of the light source below and above the classical limit corresponding to a coherent state.
The multiple scattering samples consist of TiO2 particles and the sample thickness is varied between 6 µm and 20 µm. The samples are illuminated with the squeezed light source and the total transmitted photon fluctuations are recorded with a spectrum analyzer. From these measurements the spatial quantum correlation function can be determined. We observe negative (positive) spatial correlations for incident non-classical (classical) fluctuations. The strength of the spatial quantum correlations can be tuned continuously by varying the photon fluctuations of the light source. This pronounced behavior is clearly demonstrated in figure (a). Furthermore, the spatial correlation

function is predicted to be independent of the sample thickness, which holds in the diffusive regime of multiple scattering. This behavior is experimentally confirmed as well, as shown in figure (b).

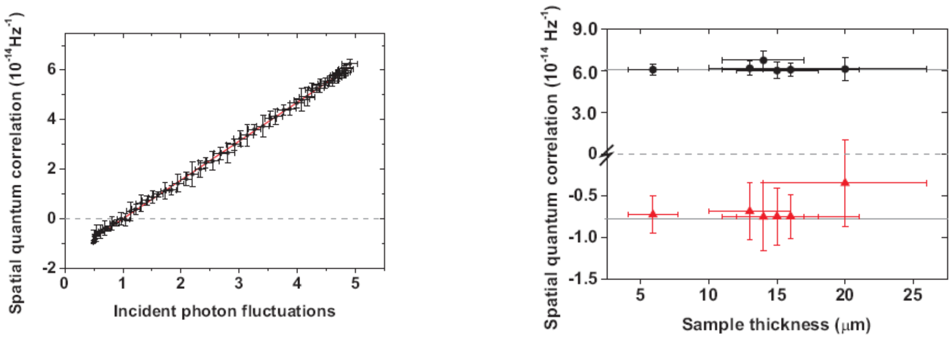


***Figure** (a) Measured spatial quantum correlation function versus photon fluctuations of the incident light beam relative to the shot noise level. Every data point represents an average over 6 different positions on the sample of thickness L = 6 μm. (b) Spatial quantum correlation function versus sample thickness. The spatial quantum correlation function is found to be independent of the sample thickness in agreement with theory (horizontal lines).*

Publications

S. Smolka, A. Huck, U. L. Andersen, A. Lagendijk, and P. Lodal, *Experimental Demonstration of Spatial Quantum Correlations in Multiple Scattering Media*, accepted for publication in Physical Review Letters (arXiv:0811.3561)

Conference presentations

S. Smolka, A. Huck, U. L. Andersen, and P. Lodal, '*Quantum optics in multiple scattering random media*', oral presentation at the meeting of the Danish Optical Society 2008 Nyborg/Denmark

S. Smolka, A. Huck, U. L. Andersen, A. Lagendijk, and P. Lodal, '*Experimental demonstration of spatial quantum correlations in multiple scattering media*', oral presentation at the International OSA Network of students 2009 (IONS-5) Barcelona/Spain

S. Smolka, A. Huck, U. L. Andersen, A. Lagendijk, and P. Lodal, '*Experimental demonstration of spatial quantum correlations in multiple scattering media*', oral presentation at the Conference on Lasers and Electro-Optics (CLEO) 2009 Baltimore/USA (accepted)

S. Smolka, A. Huck, U. L. Andersen, A. Lagendijk, and P. Lodal, '*Spatial Quantum Correlations Generated by Multiple Scattering of Squeezed Light*', oral presentation at the international conference on Electrical, Transport and Optical Properties of Inhomogeneous Media (ETOPIM) 2009 Crete/Greece

Reported progress towards Deliverable 1.1: (Unexpected extra progress)
Continuous Variable Entanglement and Squeezing of Orbital Angular Momentum States
(Partner FAU, DTU)

The simplest spatial mode that can carry orbital angular momentum (OAM) is the first order Laguerre-Gaussian (LG) mode, which produces either a left-handed or right-handed corkscrew-like phase front and a ring-like intensity profile. We have experimentally realized a setup on continuous variables quadrature entanglement between the two first-order LG modes thereby demonstrating a new type of entanglement from non-degenerate optical parametric oscillators (OPOs). The entanglement is manifested in the squeezing of the rotated modes of the Hermite-Gaussian (HG) basis, measured with a specially tailored local oscillator as shown in the figure of the schematic setup below. The OPO is pumped with Gaussian beam 532nm and seeded with a HG_10 beam at 1064nm. Down-conversion in a periodically poled KTP crystal (placed inside the cavity) produces squeezing in the seed beam (HG_10) as well as in a spatially orthogonal vacuum mode – the HG_01 mode – since its frequency is degenerated with that of the HG_10 mode. The linear interference of these modes creates entangled states of the first order LG modes. These modes are probed by a spatially tailored local oscillator and the time trace of the quadratures as function of the phase θ is shown in the inset.

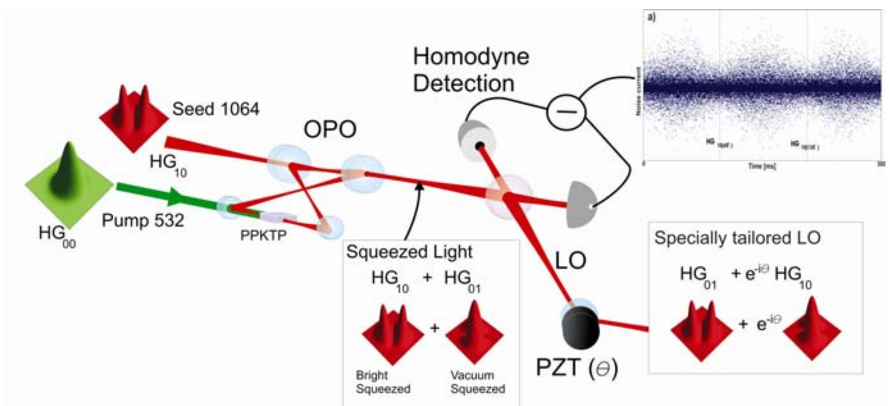


Figure: *Schematic of the experimental setup.*

As a result of the degeneracy of the LG modes, the down-conversion crystal produces correlated photons in the OAM modes, LG^{+1} and LG^{-1}, and thus creates quadrature entanglement between these two modes similarly to the production of entanglement between polarization modes. The quadrature entanglement is manifested through squeezing of the rotated modes; HG_10 and HG_01. Explicit we measured 1.6 dB of squeezing for the HG_{10} mode, 1.4 dB of squeezing for the HG_{01} mode, as illustrated in the figure below. Inserting these values into the entanglement criterion we find: $V(HG_{10})+V(HG_{01})=1.42<2$, thereby proving the existence of quadrature entanglement between the first order OAM modes.

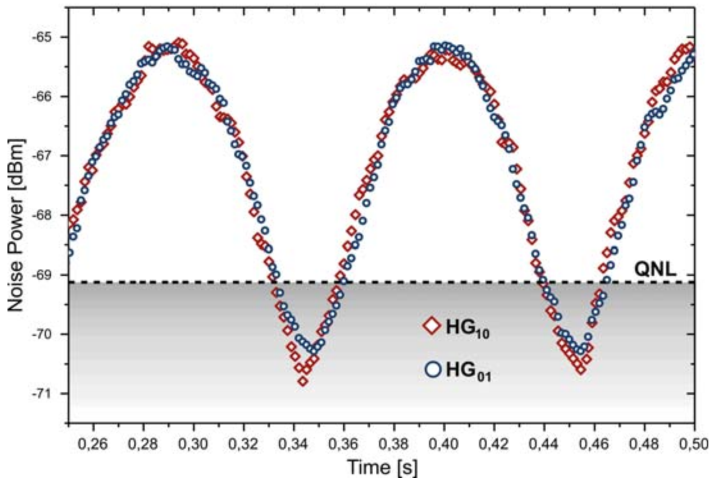


Figure: *Scan of the second-order moments of the two HG modes as a function of the phase of local oscillators prepared in the HG_10 or HG_01 modes.*

Publications

Mikael Lassen, Gerd Leuchs, and Ulrik L. Andersen, *Continuous Variable Entanglement and Squeezing of Orbital Angular Momentum States*, Phys. Rev. Lett. **102**, 163602 (2009)

Conference presentations

M. Lassen, G. Leuchs and U.L. Andersen, *Continuous Variable Entanglement and Squeezing of Orbital Angular*, Talk at the EQEC/CLEO conference, Munich, **June 14-19, 2009** (Accepted)

M. Lassen, G. Leuchs and U.L. Andersen, *Continuous Variable Entanglement and Squeezing of Orbital Angular*, Invited talk at the OSA Nonlinear Optics conference, Hawaii, **July 12-17, 2009**

Task 1.2: Exploring models of CV quantum computing

Deliverable 1.2 ***Exploration of CV quantum computing with non-Gaussian quantum states***

Status: Due month 24; Intermediate progress reported.

Partners: ULB, UP, POTSDAM

The objective of this task is to explore models of quantum computing with continuous-variable (mainly optical) carriers, in particular circuit-based and one-way quantum computing with multimode CV cluster states, and also CV quantum computing architecture that relies on “cat states”, i.e., multimode superpositions of quasi-classical states with non-positive Wigner functions. We shall assess the approach where an off-line supply of non-Gaussian auxiliary states is used as a resource together with linear optics, measurements, and feedforward, in order to effect highly non-Gaussian operations, potentially useful in the teleportation model of quantum computing. Finally, other possible computational tasks with CV quantum carriers will be carried, e.g., bit commitment.

Reported progress towards Deliverable 1.2:
Engineering quantum states and operations for traveling light beams
(Partner UP)

Partner UP investigated what are the necessary non-Gaussian resources that, combined with Gaussian operations, are sufficient for universal (probabilistic) quantum gate engineering. We have concentrated on the scenario where the quantum gates are implemented in a passive way, employing off-line generated resource states |ψ> and Gaussian operations and Gaussian measurements. We have proven that a steady supply of arbitrary pure single-mode non-Gaussian states |ψ> possessing finite expansion in Fock-state basis is sufficient for (probabilistic) implementation of any *n*-mode quantum gate.

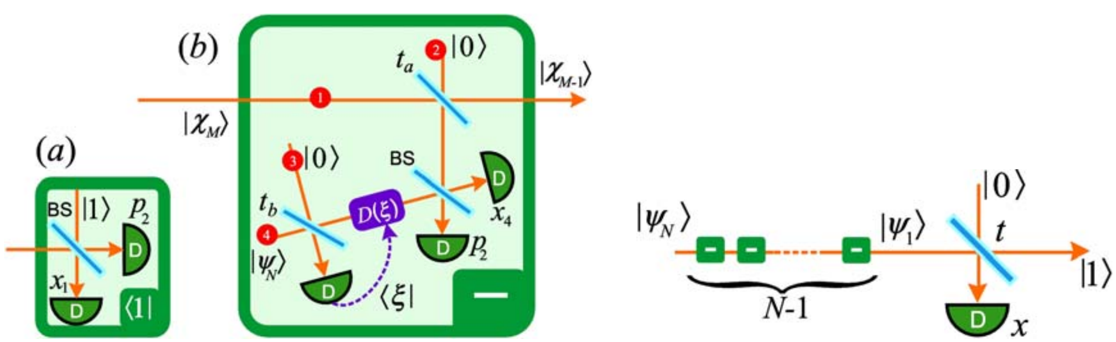


Figure: *Left panel: (a) Setup for projective measurement on a single-photon state using homodyne detectors and ancilla single-photon state. (b) Setup for generalized photon subtraction. D - homodyne detector, BS - balanced beam splitter,* $t_{a,b}$ *- beam splitter with transmittance* $t_{a,b}$*, D(ξ) - coherent displacement. Right panel: Complete setup for generation of a single-photon state by repeated application of the generalized photon subtraction operation.*

The core of our approach is the reduction of the problem to generation of single-photon Fock states |1> from the resource state |ψ>. We have provided an explicit linear-optical scheme for this latter task, see the above figure. Panel (a) shows that projection onto single-photon state can be implemented using an auxiliary single-photon state and a projection onto the CV EPR state. Panel (b) depicts a scheme for a probabilistic removal of highest Fock state form the input signal state. This procedure can be seen as a generalized version of photon subtraction operation. By repeated application of this elementary non-Gaussian operation one can convert the input state onto a superposition of vacuum and a single-photon state which can be probabilistically converted to Fock state |1> by means of a beam splitter and a homodyne detector, see figure above

To achieve a nonzero success probability of the scheme, a finite acceptance window for the measurement outcomes of the homodyne detectors has to be introduced, which leads to trade-off between operation quality and its success probability. The efficiency of the scheme can be significantly improved by optimizing the transmittances of beam splitters and the widths of the acceptance windows of homodyne measurements for each particular case. The protocol is developed primarily for travelling light modes, but the scheme could be applicable also to other physical platforms such as atomic ensembles or opto-mechanical systems. As an application we have successfully used our approach to design a scheme for a nonlinear sign gate involving only Gaussian operations and measurements and ancillary Fock states |2>.

Publications:

P. Marek and J. Fiurášek, *Resources for universal quantum state manipulation and engineering*, submitted to Phys. Rev. A.

Reported progress towards Deliverable 1.2:
Efficient continuous-variable measurement-based quantum computing
(Partner POTSDAM)

We have systematically studied the potential of CV systems in measurement-based quantum computing. First identifying obstacles that have to be overcome when thinking about quantum computing based on measurements on Gaussian states, we have proposed a systematic framework of computational schemes on the basis of local measurement on certain non-Gaussian states. Such non-Gaussian states emerge formally from a description in terms of so-called matrix product states with infinite physical dimension and finite bond dimension, to make quantum error correction possible, and overcoming the recent no-go-theorem for Gaussian error correction (see WP3). Physically, the states can be relatively feasible to be prepared with atom-field interactions using bright light, simple passive optics, and homodyning measurements only. No sophisticated measurements or complicated state transformations are needed in this scheme. Computation is eventually done in the correlation space that is associated with the resulting Gaussian states, and computation is controlled by appropriate homodyne measurements. Current work is focused on finding the most feasible experimental implementation of such ideas.

Publications:

M. Ohlinger and J. Eisert, *Efficient continuous-variable measurement-based quantum computing*, in preparation (2009).

Reported progress towards Deliverable 1.2:
Exploration of CV quantum bit commitment: Gaussian vs. non-Gaussian protocols
(Partner ULB)

Bit commitment is a cryptographic primitive with a large scope of applications ranging from two-party secure computation, e.g., secure authentication, to coin flipping. It involves two mistrustful parties: Alice wants to commit a certain bit, which should remain hidden to Bob until she reveals its value. A bit commitment protocol is said to be secure if it prevents Alice to cheat (i.e., she cannot change the value of the bit she had committed) and Bob to cheat (i.e., he cannot learn information about the bit before Alice reveals it). This primitive has been exhaustively studied in classical cryptography, where the security relies on unproven computational. The idea of quantum bit commitment (QBC) was first introduced by Bennett and Brassard in 1984, together with the famous BB84 quantum key distribution protocol. In 1993, Bennett *et al.* proposed a QBC protocol {1}, which was believed to be secure until 1996, when Mayers and independently Lo and Chau proved that it was not the case. This is the content of the *no-go theorem* for QBC, which, interestingly, is in sharp contrast with quantum key distribution for which unconditionally protocols have been exhibited.

Let us stress that this no-go theorem only applies to unconditionally secure protocols, that is, to the case where Alice and Bob have no restriction on their capabilities except those dictated by quantum mechanics. This leaves the door open to QBC protocols that could be secure under reasonable assumptions on Alice and Bob's capabilities. Such a protocol was found in the bounded-storage model, where both parties only have access to a finite-size quantum memory {2}. Another possible way around the no-go theorem is to exploit the constraints imposed by special relativity to achieve unconditional security {3}.

In a collaboration with the Laboratoire de Recherche en Informtique (LRI, Orsay, France), partner ULB has introduced QBC protocols with continuous variables, and explored whether such protocols may be found secure if both parties are restricted to use Gaussian states and Gaussian operations. Apart from being efficiently characterizable within the appropriate formalism, Gaussian states and operations can be relatively easily manipulated in the laboratory. It is therefore a very natural and important question to ask whether QBC protocols can be built with continuous variables, which could be made secure. In this preliminary work (more details will be provided at the end of the second year of COMPAS), Partners ULB has answered by the negative, and has established a *strong* no-go theorem for Gaussian QBC protocols. Specifically, for any Gaussian QBC protocol, a corresponding Gaussian cheating strategy can be exhibited. Nevertheless, this leaves open the possible existence of non-Gaussian QBC protocols that could be secure against Gaussian attacks. This is the subject of further work within COMPAS.

References:

{1} G. Brassard, C. Crépeau, R. Jozsa, and D. Langlois, in: *29th Symp. on Found. of Computer Sci. IEEE* (1993), pp. 42-52.
{2} I.B. Damgaard, S. Fehr, L. Salvail, and C. Schaffner, SIAM J. Comput. **37**, 1865 (2008).
{3} A. Kent, Phys. Rev. Lett. **83**, 1447 (1999).

Publications:

L. Magnin, F. Magniez, A. Leverrier, and N.J. Cerf, *Strong No-Go Theorem for Gaussian Quantum Bit Commitment*, in preparation (2009).

Presentations:

L. Magnin, *Strong No-Go Theorem for Gaussian Quantum Bit Commitment*, University of Calgary, Canada, May 28, 2009. [INVITED SEMINAR]

Task 1.3: Engineering non-Gaussian states of light

Deliverable 1.3: ***Generation of high photon number Fock states***
Status: Due month 24; Intermediate progress reported.

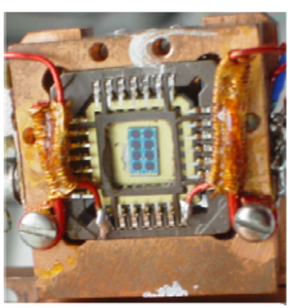
Deliverable1.4: ***Generation of monomode and multimode cat states***
Status: Due month 24; Intermediate progress reported.

Partners: CNRS/IO

The objective of this task is to address the generation of highly non-Gaussian states of travelling light beams with negative Wigner function, in particular high-N Fock states and single- or multi-mode “cat states”. These states are essential elements for CV quantum information processing, and are generally obtained using measurement-induced nonlinearities, as already demonstrated by the CNRS/IO group and others. This task should pave the way to the demonstration of CV cat-states computing, in particular the C-NOT and Hadamard gates that will be realized in WP3.

Reported progress towards Deliverable 1.3:
Cryogenic photon counters for photon-number resolving measurements
(Partner CNRS/IO)

Our experiment is using a VLPC device (see the figure below, left and right panels), which is a detector developed in the 90’s by Rockwell in order to be used with scintillating fibers. This device is the visible version of the SSPM detector. The silicon structure, doped with As impurities, allows an avalanche amplification with low gain dispersion {1}. This performance allows one to count several photons the same way as a Photo Multiplier Tube and, thanks to the Si properties, with a very good quantum efficiency. Therefore, this detector is a good candidate for multi-photon quantum optics experiments {2}.



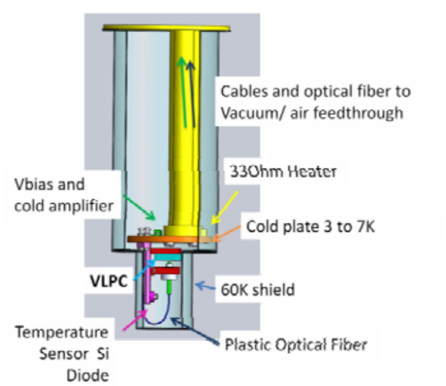


Figure: *Left panel: VLPC chip on its copper mount (only one out of the 8 pixels is used). Right panel: Inside view of the detector mounted in the pulsed tube cryostat.*

The detector has been integrated in the cryostat and we are currently optimizing of the performances (this requires mechanical and electronics improvement).

Presently, we have observed an avalanche gain of about 35000 e-/ counted photon, which is a quite acceptable value, in good agreement with the literature. On the other hand, the estimated VLPC efficiency (ratio counted photon / incident photon) is only 5%, and has to be improved by a better alignment of the optical fiber which brings the light from the source at room temperature, down to the detector at liquid helium temperature. As shown in the figure below, the number of discriminated photons is up to 3, but the resolution is not very good. This is mostly attributed to noise in the electronics, and improvements are also under way.

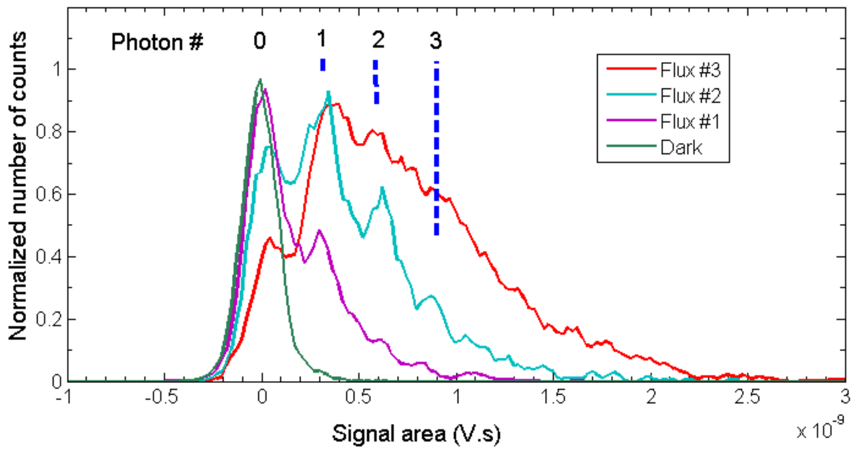


Figure: *The graph represents the area signal normalized histogram (2000 acquisitions) for 3 different light levels and dark signal. The 850nm pulses are 2ns FWHM at 10 kHz, the VLPC chip is at 6 K. Up to 3 photon picks are distinguishable on Flux #3.*

References:

{1} G.B. Turner et al., SCIFI 93, Workshop on Scintillating Fiber detector, October 24-28, 1993, pp. 613-629.
{2} Edo Waks et al., IEEE Journal of selected topics in quantum electronics, Vol 9, N°6 (2003).

Reported progress towards Deliverable 1.4:
Preparation of non-local superpositions of quasi-classical light states
(Partner CNRS/IO)

Local superpositions of free-propagating coherent states were previously realized experimentally, but their applications were limited by their extreme sensitivity to losses, and by the lack of quantum gates for coherent qubit rotations. During this reporting period partner CNRS/IO has demonstrated a simple approach to generate strongly entangled non-local superpositions of coherent states, through a very lossy quantum channel. Such superpositions can be used to implement a coherent qubit rotation gate, and to teleport those qubits over long distances. The generation scheme can be extended to create entangled coherent superpositions with arbitrarily large amplitudes.

Besides their fundamental interest, arbitrary coherent superpositions ($a|\alpha\rangle + b|-\alpha\rangle$) can be used as qubits carrying quantum information, if $|\alpha\rangle$ and $|-\alpha\rangle$ are sufficiently distinguishable ($|\alpha|^2 > 2$). They present many advantages compared to discrete-variable qubits ($a|0\rangle + b|1\rangle$), allowing one to circumvent the fundamental limits of discrete-variable quantum teleportation, or to perform loophole-free Bell tests (see Task 1.1).

So far, their applications suffered from two major problems. One was the difficulty to build associated logic gates: arbitrary qubit rotations were believed to require either unrealistically strong non-linear interactions, or very resource-consuming repeated infinitesimal rotations. The other was more fundamental: the complex structure of these states, while offering many benefits, makes them notoriously fragile. The approach demonstrated by the CNRS/IO circumvents the fragility of these states, typically described with continuous quadrature variables, by using the robustness offered by discrete-variable QIP. It consists in probabilistic entanglement swapping, similar to the discrete-variable DLCZ protocol, where losses decrease the success rate instead of the state quality. We create long-range entanglement by subtracting a delocalized single photon from initially separable states, see the next figure.

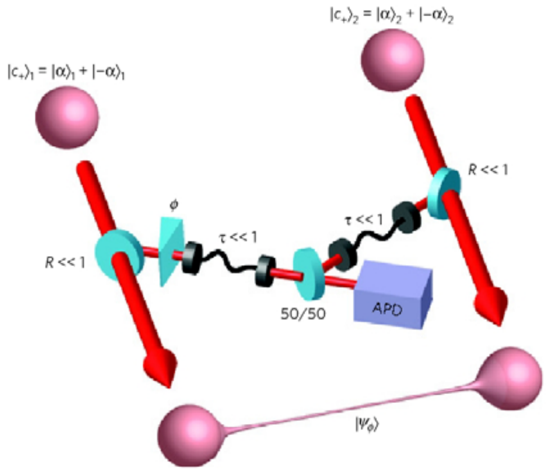


Figure: *Remote entanglement of two independent cat states through lossy channels. The entanglement is created by non-local photon subtraction, by interfering small fractions R of each pulse, phase-shifted by f, on a 50/50 beamsplitter. Then an APD photon detection in one of the outputs prepares the entangled cat-like state, useful as a resource for long- distance quantum teleportation and phase-space rotations of coherent qubits.*

The experimental scheme and examples of the generated Wigner functions (which are at the same time negative and entangled) are shown respectively in the upper and lower figures on the next page. This scheme overcomes, to some extent, the high sensitivity to losses encountered in many continuous-variable QIP protocols. By using the specific discrete-variable advantage of discarding those events where photons were lost, we have shown that sophisticated continuous-variable entangled resources can be prepared despite strong losses in quantum channels. These states may be used as ancillas to implement arbitrary controlled qubit rotations, required in most QIP protocols, without needing strong nonlinearities or extensive experimental resources.

Publications:

A. Ourjoumtsev, F. Ferreyrol, R. Tualle-Brouri, and P. Grangier, *Preparation of non-local superpositions of quasi-classical light states*, Nature Phys. **5**, 189-192 (2009).

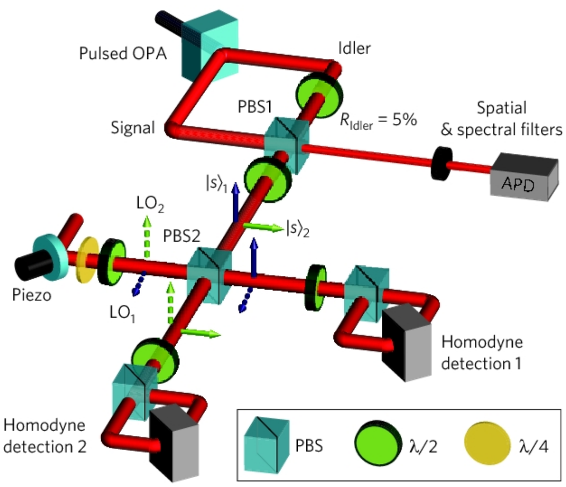


Figure: *Experimental setup. The signal and idler from a pulsed OPA are recombined on a polarizing beam-splitter PBS1 to produce two independent squeezed light pulses* $|s>_1$ *and* $|s>_2$ *(close to even "Schrödinger kittens"), while the other channel of PBS1 is used as the conditioning channel to entangle them. The two entangled beams, co-propagating with orthogonal polarizations, are separated and mixed with two local oscillators LO1 and LO2 on PBS2, and finally detected by two independent homodyne detections.*

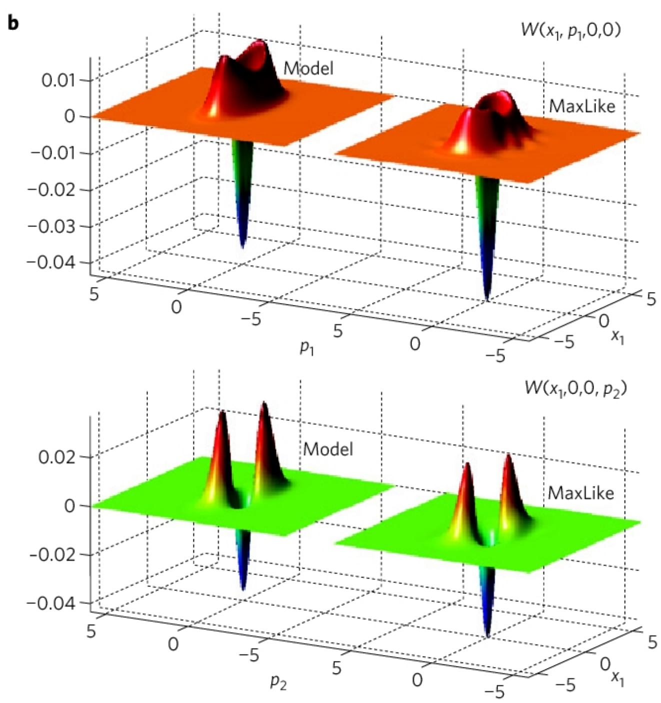


Figure: *An example of a cut of the experimentally reconstructed Wigner function of the generated entangled state (corrected for homodyne losses using MaxLik estimation procedure), compared with the prediction of our analytical model, which takes into account all major sources of decoherence in the experiment.*

Task 1.4: **Investigating measurement-induced CV information processes**

Deliverable1.5: ***Measurement-induced nonlinear operations***
Status: Due month 36 no progress reported yet.

Deliverable 1.6: ***Detector process tomography***
Status: Due month 24; Intermediate progress reported.

Partners: CNRS/IO, ULB, UP, POTSDAM

The objective of this task is to analyze measurement-induced nonlinear effects that may be attained by combining linear coupling, single-photon counting, homodyne detection, feedforward or conditioning. Such nonlinear operations are crucial to address universal CV quantum computation and CV entanglement purification. A major result has been obtained during Y1 in this direction, which is the demonstration of the creation of "remote entanglement" through a very lossy channel. Such a scheme will then be exploited in WP3 for the realization of computing protocols. In addition, the detector process tomography will be another main research direction in this task.

Reported progress towards Deliverable 1.6:
Tomography of quantum detectors
(Partner POTSDAM)

Quantum properties only reveal themselves through measurement techniques. In addition, most quantum information applications both computational and cryptographic, rely on a certain knowledge of the measurement apparatuses involved. The assumption of a fully characterized detector completely also underlies both quantum state tomography (QST) and quantum process tomography (QPT). State tomography has become an important tool for characterizing states, partially due to the realization that non-classical states are a resource for performing tasks such as enhanced precision metering, quantum communication, and quantum computation.

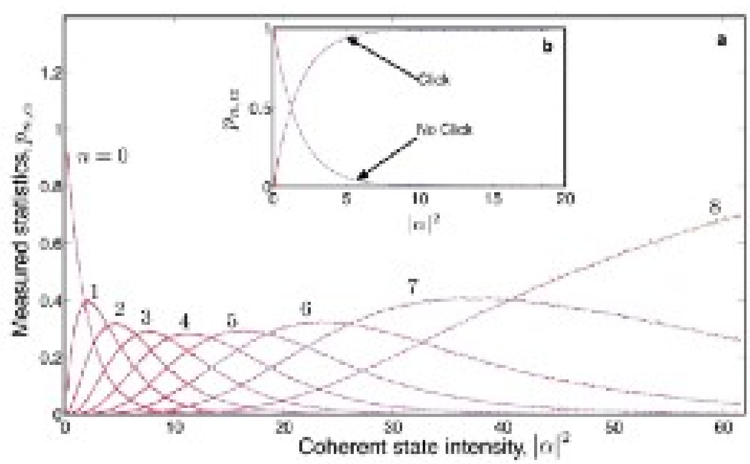


Figure 1: *The detector tomography data. The outcome statistics (red dots) are measured as a function of the coherent state magnitude and form an estimate of $p_{n,\alpha}$ for each detector outcome n (number of clicks).*

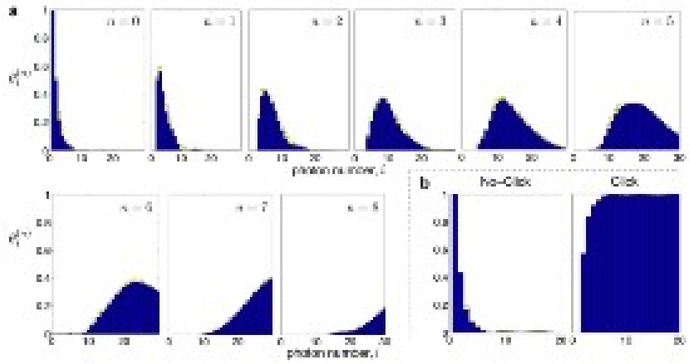


Figure 2: *The optimal physical POVMs. We present the diagonals of the reconstructed POVMs represented in the photon-number basis for (a) the photon-number resolving TMD and (b) the binary APD detector.*

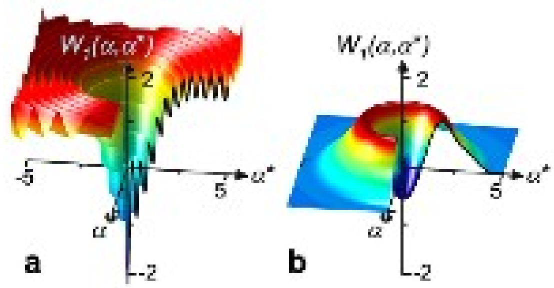


Figure 3: *The Wigner functions of the 'one click' detector outcomes. From the diagonal elements of π_1 for the APD (a) and TMD (b) one can generate the Wigner function representing their measurement of the optical mode.*

We have now performed a full first detector tomography that makes no a-priori and possibly unjustified assumptions on the detector device. We unambiguously find the best POVM elements that describe the measurement data, dealing with the intrinsic ill-conditioning encountered in such problems, using convex optimization ideas. A sample of the recorded data is shown in Figure1. The results of the POVM reconstruction are shown in Figures 2 and 3. Such a detector tomography is done for several photon detecting or counting detectors, exploring ideas of multiplexing. Specifically, a variant that brings together CV and discrete-variable approaches, in form of weak homodyning, is exhibited, which can be viewed as photon counting with a weak phase reference. Once characterized, one can use such detectors in CV entanglement distillation schemes and the preparation of non-Gaussian states, being relevant for other deliverables within this project.

Publications:

J. Lundeen, A. Feito, H. Coldenstrodt-Runge, T.C. Ralph, C. Silberhorn, J. Eisert, M.B. Plenio, and I.A. Walmsley, *Tomography of quantum detectors*, Nature Phys. **5**, 27 (2009).

H.B. Coldenstrodt-Ronge, J.S. Lundeen, K.L. Pregnell, A. Feito, B.J. Smith, W. Mauerer, Ch. Silberhorn, J. Eisert, M.B. Plenio, and I.A. Walmsley, *A proposed testbed for detector tomography*, J. Mod. Opt. **56**, 432 (2009).

A. Feito, J.S. Lundeen, H. Coldenstrodt-Ronge, J. Eisert, M.B. Plenio, and I.A. Walmsley, *Measuring measurement*, in preparation (2009).

Workpackage 2: Design of atomic components of CV quantum computing

Period covered: from 01/04/08 to 31/03/09
Organisation name of lead contractor for this workpackage: NBI
Other contractors involved: CNRS/ENS, MPG, UP, USTAN, CNRS/IO

Progress towards objectives of WP2 during year 1 of the project

Partner NBI demonstrated a low noise measurement of one component of the collective pseudo-spin of a cloud of 10^5 cold and dipole trapped Cesium atoms using a novel dual-color interferometric probing technique that allows for the cancellation of numerous classical noise sources. Using this technique the atoms were prepared in a strongly entangled collective squeezed state that can be used to improve quantum precision measurements or can serve as a low noise initial state for a quantum memory protocol. Partner CNRS/ENS developed an EIT-based three-level adiabatic passage protocol for quantum memory using a Cesium vapour in a cell. Quantum storage and retrieval of the two non-commuting quadratures of a small coherent state, made of a *single sideband* of the control field, was successfully demonstrated. Partner UP proposed and theoretically analyzed a scheme for conditional preparation of arbitrary states of an atomic ensemble by quantum non-demolition interaction with light prepared in a specific highly non-classical quantum state. This allows one to implement operations on atomic ensemble that are not easy to perform directly on atoms, but are more feasible on light.

Partner MPG showed that cold atoms in optical lattices can be used to perform an entangling unitary operation on the transferred atomic excitations. After the release of the quantum atomic state, the protocol results in a deterministic two qubit gate for photons. Partners MPG and NBI developed two schemes in which N-particle entangled states can be created and verified in experiments using superradiant Raman scattering of laser light from a Bose-Einstein condensate. The first scheme creates entanglement between stationary and flying qubits, atoms and light, while the second scheme produces entanglement between two condensates in different momentum states. Partner MPG also developed a theoretical framework to describe the collective emission of light by entangled atomic states in the low-excitation regime, where most of the atoms are initially in the ground state. It was shown how to observe collective phenomena with ultracold atoms in optical lattices and how these ideas can be used to generate photonic states that are useful for quantum information processing.

Partner USTAN investigated the influence of correlated losses on quantum states generated as a result of the cross-Kerr nonlinear interaction between two modes. Partner NBI made significant steps towards developing a new CV quantum repeater based on non-Gaussian ’Schrödinger cat’ states. Partner MPG addressed the problem of creating a long-distance entangled state between two stations of a network, where neighboring nodes are connected by noisy quantum channels. It was shown that any two stations can share an entangled pair if the effective probability for the quantum errors is below a certain threshold. In contrast to the conventional quantum-repeater schemes, there is no need to store the qubits in quantum memory for a long time: this protocol is a one-shot process involving one-way classical communication.

Task 2.1: Engineering and manipulating states of an atomic quantum memory

Deliverable2.1: ***Engineering and manipulating states in atomic quantum memory***

Status: Due month 36; Intermediate progress reported.

Partners: NBI

The focus of this task is to develop techniques for engineering and/or manipulating the states of an atomic memory. In particular, a combination of photon counting and homodyne detection on a squeezed light beam interacting with the atomic ensemble should allow to generate a large variety of highly-nonclassical atomic states. The state engineering schemes shall then be generalized to methods for implementing various non-linear operations on the atomic memory states. The generation and manipulation of highly non-classical states of atomic memory is essential for advanced CV quantum information processors such as quantum repeaters.

Reported progress towards Deliverable 2.1:
Mesoscopic atomic entanglement for precision measurements beyond the standard quantum limit (Partner NBI)

A goal of Task 2.1 is the engineering of non-Gaussian states of atoms. Partner NBI aims to achieve this goal by performing a two step process: Light interacts with an atomic ensemble and it becomes entangled with the atoms. A subsequent measurement on the light then allows either the conditional or (with feedback) the deterministic preparation of an atomic quantum state. A critical and difficult point in performing this measurement is that the outcome of the optical measurement has to be strongly correlated with the quantum state of the atoms and is not dominated by classical noise.

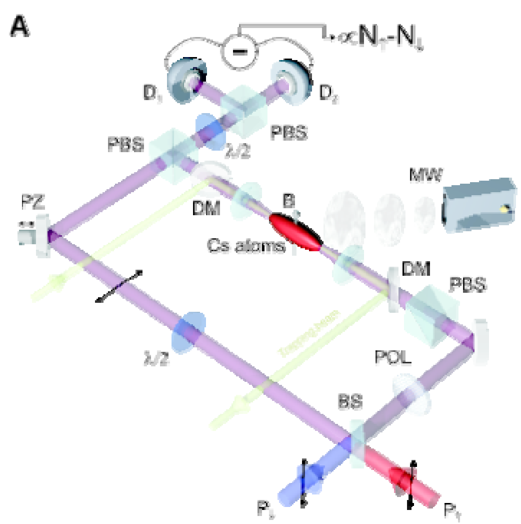


Figure 1: *~ 10^5 Cs atoms are held in one arm of a Mach-Zehnder interferometer by a trapping beam folded by two dichroic mirrors (DM). The atoms are prepared in a coherent superposition of the clock states |↑> and|↓>, by applying a microwave (MW) π/2-pulse. Two linearly polarized probe beams $P_\uparrow$ and $P_\downarrow$ enter the interferometer via separate ports of the input beam splitter (BS). The probes acquire phase shifts proportional to the number of atoms in the clock states $N_\uparrow$ and $N_\downarrow$, respectively. The combined phase shift ($(N_\uparrow - N_\downarrow)$) of the two probes is measured in a balanced homodyne configuration.*

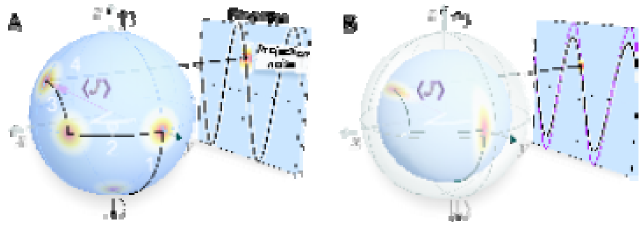


Figure 2: *A Bloch sphere representation of a Ramsey sequence with atoms initially in the state |↓> (south pole). A microwave π/2 pulse rotates the Bloch vector to the equator bringing each atom into a superposition state |↑>+|↓>, (1). This Coherent Spin-State (CSS) is characterized by quantum fluctuations* $(\delta J_z)^2=(\delta J_x)^2=N_A/4$ *illustrated as a fuzzy disk. Then the atoms evolve freely for a time T and the Bloch vector precesses about the z axis (2). φ is recorded after a second π/2-pulse (3) by measuring the population difference (4):* $\cos \varphi=(N_{\uparrow}- N_{\downarrow})/N_A$. *Projection noise will result in an uncertainty of the Ramsey fringe position. B - The effect of projection noise in Ramsey spectroscopy can be reduced by applying an SSS generated via a dispersive QND measurement.*

During the first year of the project, partner NBI was able to realize such a low noise measurement by measuring one component of the collective pseudo-spin of a cloud of 10^5 cold and dipole trapped Cesium atoms. The atoms' state dependent refractive index is measured using a novel dual-color interferometric probing technique (Fig. 1) that allows for cancellation of numerous classical noise sources and offers a much more ideal quantum-non-demolition interaction than previous proposals. Using this technique we were able to prepare the atoms into a strongly entangled collective state – albeit with Gaussian statistics. The produced squeezed atomic state can be used to improve quantum precision measurements (atomic clocks, Ramsey spectroscopy, see Fig. 2) beyond the standard quantum limit or it can serve as a low noise initial state for a quantum memory protocol. As this result confirms that we have achieved the necessary strength and precision of control of the interaction between atoms and light we consider this result an important tool towards producing non-Gaussian atomic states (like pseudo-spin Cat states).

To fully characterize and confirm the preparation of a certain atomic state, it is however not sufficient to only be able to measure one component of the atomic pseudo-spin. Therefore a method for characterizing the atomic quantum state had to be developed: By using a microwave π/2-pulse to perform a "beam splitter" transformation of the atomic state and by using quantum interference of the quantum state to be analyzed with an atomic coherent spin state we develop an atomic analogue to homodyne tomography, which will be used to characterize the engineered atomic quantum state. Current work on the experiment aims to characterize and reduce the influence of phase noise in our microwave oscillator and intensity noise in our dipole laser to increase the precision to the standard quantum limit. In parallel we started to implement changes in the experimental setup necessary to create atomic Fock states by single-photon detection using the Duan-Lukin-Cirac-Zoller protocol as a first example of an atomic state with a negative Wigner function. Filter cavities to separate the excitation pulse from the spontaneous emission have been designed and tested, and changes in the Mach-Zehnder interferometer have been implemented to allow to use for these experiments the clock transition $|F=3,m_F=-1\rangle \leftrightarrow |F=4,m_F=1\rangle$.

We have also started to explore in how far the very large achievable coupling between light and a quantum degenerate atomic sample can be harnessed to prepare nontrivial states of the atomic sample. We routinely produce Bose-Einstein condensates (BEC) in a magnetic trap containing 1.5×10^6 Rubidium atoms. By super-radiant Rayleigh scattering in a backward geometry a mesoscopic number of momentum excitations is created and stored inside the ensemble, strictly correlated with the number of backscattered photons. The underlying interaction Hamiltonian is analogous to spontaneous parametric down-conversion of pump photons into backscattered and recoiling photon-atom pairs. The existence of strong correlations is fairly trivial from a theoretical point of view (conservation of linear and angular momentum). They can, however, be used in for QIP purposes only if they are detected reliably and quantitatively. A series of experiments has been performed to count backscattered photons and recoiling atoms for different interaction parameters and proportionality is demonstrated. The fluctuations in the detected number difference are, at present, far above the interesting quantum regime and various technical noise sources have been identified which spoil the possible detection of entanglement. The most prominent source of noise is instability of the atom counting sensitivity and steps are being taken to overcome this limitation by a better stabilization of laser frequency. From the experimental results atom-atom collisions in our dense atom clouds have been identified as important decoherence channels. First tests with more dilute clouds show that the influence of collisions can be suppressed and a new measurement of correlations with dilute samples and improved detection stability is planned for the second year of the project.

Publications:

J. Appel, P.J. Windpassinger, D. Oblak, U.B. Hoff, N. Kjaergaard, E.S. Polzik, *Mesoscopic atomic entanglement for precision measurements beyond the standard quantum limit*, arXiv:0810.3545, (2008), to appear in PNAS.

Reported progress towards Deliverable 2.1:

Scheme for conditional preparation of arbitrary states of atomic quantum memory

(Partner UP)

Partner UP has proposed and theoretically analyzed a scheme for conditional preparation of arbitrary states of atomic quantum memory for light. The general idea behind the devised protocol is to manipulate the atomic state by quantum non-demolition (QND) interaction with light that has been previously prepared in a specific highly non-classical quantum state. This technique allows us to employ QND interaction to implement operations on atomic ensemble that are not easy to perform directly on atoms, but are more feasible on light. In particular, we have shown that by using light beam prepared in a photon-subtracted squeezed vacuum state we could implement an operation on the atomic memory that is similar to the single-photon subtraction/addition.

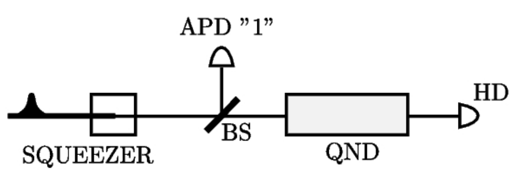


Fig. 1: *Atom-light interaction setup.*

The scheme is shown in Fig. 1. Light is prepared in a squeezed vacuum state in the squeezer and then a tiny portion of the light beam 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, phase quadrature of the output light beam is measured by homodyne detector (HD) and conditioninng on the measurement outcome is performed.

This elementary non-Gaussian operation can be combined with coherent displacements of atomic state and repeated several times to conditionally generate a wide class of highly non-classical states of the atomic quantum memory. The resulting scheme depicted in Fig. 2 is somewhat analogous to protocols for generation of arbitrary superpositions of Fock states of traveling light beams by repeated photon addition or subtraction, but it exhibits important differences due to the QND coupling and the need for conditioning on the outcomes of homodyne detection on the output light beam.

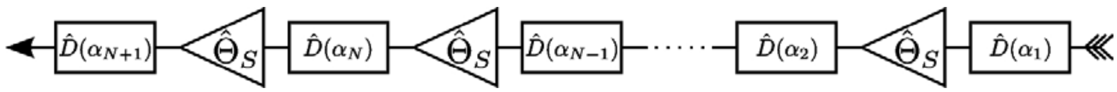


Fig. 2: *Schematized multiple interaction scheme for generation of superpositions of first N+1 atomic Dicke states. The procedure consists of sequence of N non-Gaussian operations combined with N+1 coherent displacements of the atomic state.*

Several numerical simulations have been performed to verify the functionality of the scheme. We have analyzed in detail influence of various relevant experimental parameters on the performance of the protocol and we have also investigated methods to maximize the trade-off between fidelity of prepared state and success probability of the scheme. We have found that the performance of the protocol can be significantly improved by judicious choice of the acceptance window for results of homodyne detection and by applying feedback displacement on atoms depending on the outcome of homodyne detection on light. It was demonstrated that using coupling of light to arbitrary rotated atomic quadratures can be very useful as it allows to prepare an arbitrary state of the memory. Also, an alternative single-step scheme for preparation of atomic memory state was suggested based on directly imprinting a state of light beam onto quantum memory.

Publications

K. Lemr and J. Fiurášek, *Conditional preparation of arbitrary superpositions of atomic Dicke states,* Phys. Rev. A **79**, 043808 (2009).

Task 2.2: Realization of high-efficiency long-lived quantum memories

Deliverable2.2: ***Light-atoms quantum interface for quantum information processing***

Status: Due month 24; Intermediate progress reported.

Partners: CNRS/ENS, MPG, NBI

The goal is to ivestigate and experimentaly assess novel principles for the realization of long-lived quantum memories and to determine the performance of the proposed mapping protocols for memory storage and retrieval of non-Gaussian states of light. In parallel, new schemes for high-efficiency quantum memories will be developed based on the off-resonant interaction of light with cold Cesium atoms held in a magneto-optic trap.

Reported progress towards Deliverable 2.2:
Reversible Quantum Interface for Tunable Single-sideband Modulation
(Partner CNRS/ENS)

The CNRS/ENS group has performed a detailed study of the quantum storage process in Cesium vapour. The aim is to store two non commuting variables of light, such as two quadratures, in the atomic coherence of the ground state. The three-level adiabatic passage protocol has been tested on Cesium vapour in a cell. Quantum storage was demonstrated. Improved performances are expected from further studies of the ground state decoherence and from the implementation of cold atomic ensembles.

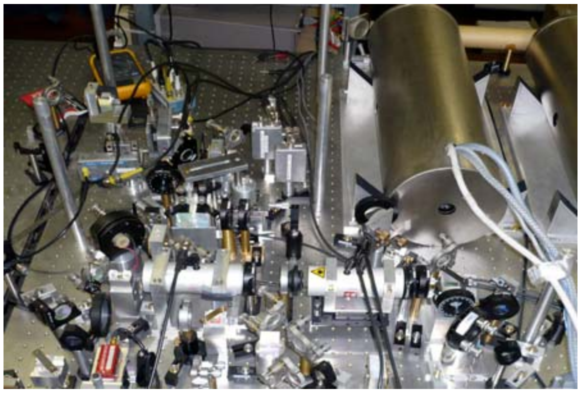


Fig. 1: *Experimental set-up*

The storage protocol relies on three-level atoms in a Lambda configuration, with two ground states and one excited state. Two light fields, the control field and the signal field interact with the atoms, with frequencies close to resonance with the two atomic transitions. For optimal efficiency, the two-photon resonance must be fulfilled. The control field is a strong, classical field that makes the medium transparent by way of EIT for the signal field to be stored, which is much weaker. If the control field is strong enough, the atomic medium becomes transparent for the signal field, and the refractive index acquires a very high slope as a function of frequency in the vicinity of the one-photon resonance. Thus the group velocity for the signal field is strongly reduced and the signal pulse can even be stopped.

When the signal pulse in entirely inside the atomic medium and after a write time that is on the order of the characteristic interaction time between atoms and fields, the control and signal fields can be switched off. The two quadratures of the signal field are then stored in two components of the ground state coherence. For read-out, the control field is turned on again. The medium emits a weak pulse, similar to the original signal pulse that goes out of the medium together with the control field. A first step of the quantum memory demonstration has been performed using Cesium atomic vapour on the $6S_{1/2}$ (F=3)-$6P_{3/2}$(F=2) transition. A paraffin coated cell is used to preserve the ground state coherence and the cell is placed in a three-layer magnetic shield, containing coils producing a ~1.Gs magnetic field (see experimental setup in Fig 1). In order to fulfil the two-photon resonance, the detuning between the control and signal beams is set to be equal to the Zeeman shift between the two concerned sub-levels. A specific detection system was built, in order to precisely measure the mean values and the variances of the outgoing signal after storage.

We have shown that the experiment allows to store the two quadratures of a signal made of a faint coherent field in the atomic ensemble and then to retrieve it (see Fig. 2). The storage efficiency decreases with the storage time, with a time constant ~10µs, due to spin relaxation in the ground state, in particular because of stray magnetic fields and collisions. Further studies are planned in order to improve the storage time.

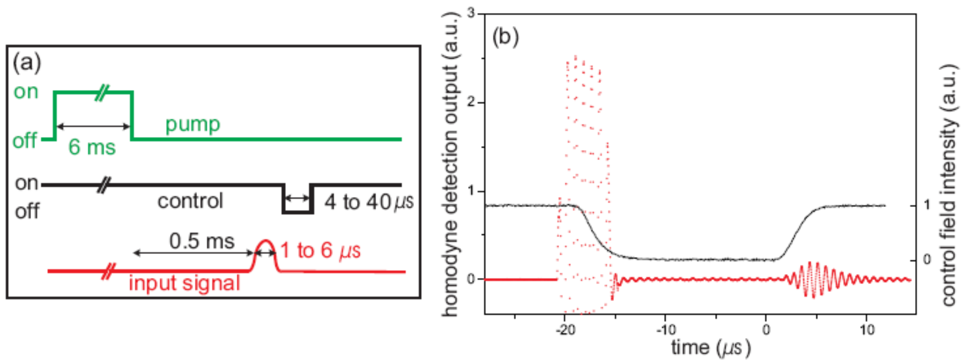


Fig. 2: *(a) Detail of the experimental sequence. (b) Temporal profile of the control field during the writing, storage and reading stage (solid line), together with the homodyne detection output current (dots) for a 4 µW input pulse, in arbitrary units.*

A critical feature for a quantum memory is the noise characteristics of the outgoing signal. A detailed study of the variance of the outgoing signal has been performed. It shows that very little excess noise is added when the control field is not too strong. In this case, application of the T-V criterion shows the memory does operate in the quantum regime. An experiment aiming at the storage of a squeezed vacuum field is under way. Squeezed vacuum on a broad frequency spectrum has been produced at 852 nm for this experiment.

In summary, partner CNRS/ENS has demonstrated quantum storage and retrieval of the two non-commuting quadratures of a small coherent state, made of a *single sideband* of the control field. The optimal response frequency of the medium for storage can thus be adapted to the frequency to be stored by changing the magnetic field, keeping the EIT window rather narrow. When a modulation made of two symmetrical sidebands must be stored, the storage may be hampered by the finite bandwidth of the EIT window. Storing the two sidebands in two separate ensembles is thus a promising method for quantum memory with a widely adjustable frequency. This method can also be applied to a squeezed field, after separating the two sidebands using an interferometer. After read-out, the two sidebands can be recombined.

Publications:

J. Cviklinski, J. Ortalo, J. Laurat, A. Bramati, M. Pinard, E. Giacobino, *Reversible Quantum Interface for Tunable Single-sideband Modulation*, Phys. Rev. Lett. **101**, 133601 (2008).

S. Burks, J. Ortalo, A. Chiummo, X. Jia, F. Villa, A. Bramati, J. Laurat, and E. Giacobino, *Vacuum squeezed light for atomic memories at the D2 cesium line*, Optics Express **17**, 3379 (2009).

Conferences:

E. Giacobino, *Quantum field storage in an atomic medium* , Laser Physics Conference LPHYS 08 (Trondheim, Norway , 30 June-4July. 2008). [INVITED TALK]

E. Giacobino, *Manipulation of quantum variables in atoms and semiconductors*, Quantum Manipulation of photons and atoms workshop (Pekin, Shanghai, China 14-22oct 2008), [INVITED TALK].

J. Laurat, *Matter-matter entanglement for quantum networks*, International conference on quantum communication, measurement and computing QCMC08 (Calgary, Canada, August 2008). [INVITED TALK]

Reported progress towards Deliverable 2.2:
Creation, verification and purification of entanglement between atoms and light by means of superradiant light scattering from Bose Einstein Condensates
(Partners MPG and NBI)

Two schemes were developed in which N-particle entangled states can be created and verified in experiments using superradiant Raman scattering of laser light from a Bose-Einstein condensate. The first scheme creates entanglement between stationary and flying qubits, atoms and light, the second scheme produces entanglement between two condensates in different momentum states. The second scheme takes advantage of leaving the Gaussian realm and features probabilistic entanglement distillation.

Publications:

C. A. Muchik, E.S. Polzik, and J.I. Cirac, *Detecting entanglement in two mode squeezed states by particle counting,* arXiv:0806.3448.

Task 2.3: Investigating alternative schemes for photonic and/or atomic quantum gates

Deliverable2.3: ***Interfacing light with atoms in optical lattices and trapped ions***
Status: Due month 24; Intermediate progress reported.

Deliverable2.4: ***Alternative methods for generating non-Gaussian states using Kerr nonlinearity***
Status: Due month 24; Intermediate progress reported.

Partners: MPG, USTAN, CNRS/IO

The objective of this task is to explore novel effects that may potentially be exploited in order to get a very high nonlinear effect. In particular, we will investigate the cross-Kerr effect that arises in an Electromagnetically Induced Transparency-type interaction of light with an atomic system. Another research avenue that will be pursued consists in exploring the possibilities offered by atoms trapped in optical lattices. These lattices could be used to create specific photonic states, useful for CV information processing.

Reported progress towards Deliverable 2.3:
Collective generation of quantum states of light by entangled atoms
(Partner MPG)

A theoretical framework to describe the collective emission of light by entangled atomic states was presented by partner MPG. The theory applies to the low-excitation regime, where most of the atoms are initially in the ground state, and relies on a bosonic description of the atomic excitations. In this way, the problem of light emission by an ensemble of atoms can be solved exactly, including dipole-dipole interactions and multiple light scattering. Explicit expressions for the emitted photonic states are obtained in several situations, such as those of atoms in regular lattices and atomic vapors. The directionality of the photonic beam, the purity of the photonic state, and the renormalization of the emission rates are determined. It is also shown how to observe collective phenomena with ultracold atoms in optical lattices and how these ideas can be used to generate photonic states that are useful in the context of quantum information.

Publications:
D. Porras and J. I. Cirac, *Collective generation of quantum states of light by entangled atoms*, Phys. Rev. A **78**, 053816 (2008).

Reported progress towards Deliverable 2.3:
Exploring interaction of light with atoms in optical lattices
(Partner MPG)

The mapping of photonic states to collective excitations of atomic ensembles is a powerful tool which finds a useful application in the realization of quantum memories and quantum repeaters. It is shown that cold atoms in optical lattices can be used to perform an entangling unitary operation on the transferred atomic excitations. After the release of the quantum atomic state, our protocol results in a deterministic two qubit gate for photons. The proposed scheme is feasible with current experimental techniques and robust against the dominant sources of noise.

Furthermore, a simple set-up corresponding to the matter-wave analogue of impurity atoms embedded in an infinite photonic crystal and interacting with the radiation field was introduced. Atoms in a given internal level are trapped in an optical lattice, and play the role of the impurities. Atoms in an untrapped level play the role of the radiation field. The interaction is mediated by means of lasers that couple those levels. By tuning the lasers parameters, it is possible to drive the system through different regimes, and observe phenomena like matter wave superradiance, non-Markovian atom emission, and the appearance of bound atomic states.

Publications:

I. de Vega, D. Porras, and J.I. Cirac, *Matter -wave emission in optical lattices: Single particle and collective effects*, Phys. Rev. Lett. **101**, 260404 (2008).

C. A. Muchik, I. de Vega, D. Porras, and J.I. Cirac, *Quantum processing photonic states in optical lattices,* Phys. Rev. Lett. **100**, 063601 (2008).

Reported progress towards Deliverable 2.4:
Influence of modal loss on the quantum state generation via cross-Kerr nonlinearity
(Partner USTAN)

Decoherence is a main practical obstacle to implementations of schemes using Kerr and cross-Kerr nonlinearities. A genuine example of quantum state degradation due to losses is a decoherence of a quantum superposition state, the effect drastically enhanced if speaking of a macroscopic superposition state of the Schr¨odinger cat type. Photon losses turn this superposition into statistical mixture of two coherent states with the rate proportional to the square modulus of the amplitude of these states. Partner USTAN has explored an aspect of the decoherence which has been seldom discussed when considering an influence of losses on states generated via Kerr nonlinearity: losses arising in the process of generation and not due to propagation of the generated state via lossy channels. They have pointed out to a feature that might be quite significantly pronounced in modern schemes of generating large Kerr nonlinearity: the modal loss can be strongly correlated. Indeed, the modes occupy the same volume and interact with the same physical systems which form the reservoirs. Also, if the Kerr-nonlinearity scheme implies a sufficiently strong dispersive coupling of light modes to emitters, then coupling of these emitters to dissipative reservoirs might also appear to be quite strong. As a result, this would mean strongly correlated modal losses. Coupling to correlated reservoirs can drastically change state dynamics in comparison with loss to uncorrelated reservoirs. Figure 1 below illustrates this pronounced difference.

In its work, partner USTAN has demonstrated both how the correlated loss arises via Kerr nonlinear process, and how it affects the generated states. For this purpose the analytic solution has been derived using the formalism of superoperators in thermofield notation. On a number of examples, partner USTAN showed how the correlated loss enhances and creates intermodal correlations and even entanglement, and might lead to generation of entangled states quite different from those generated in the same scheme without loss. Correlated loss can result in the significantly enhanced robustness of the generation scheme .

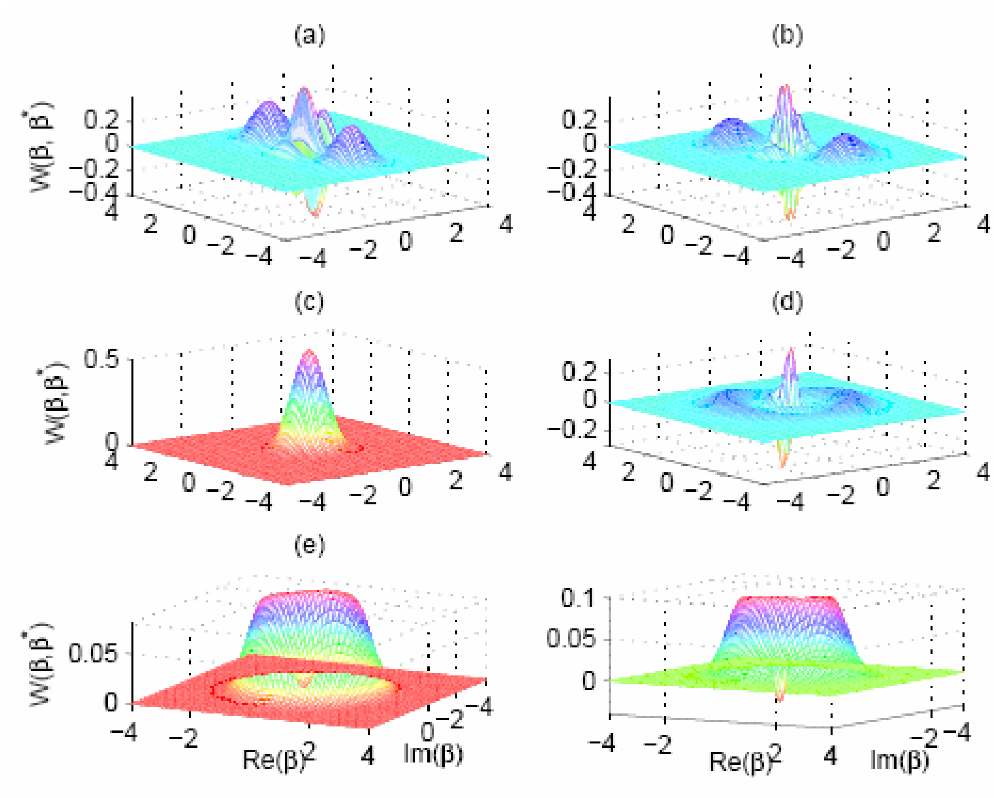


Fig. 1: *Examples of the Wigner function for the conditioned cat state using cross-Kerr interaction. Figure (a) corresponds to absence of loss. Figure (b) corresponds to the perfectly correlated loss; Figures (c) and (e) correspond to the different completely uncorrelated loss. Figures (d) and (f) correspond to the different partially correlated loss.*

As an example, in the scheme for generating non-classical states suggested by partner USTAN earlier, two coherent states interact via cross-Kerr effect in a non-linear medium and subsequently the x-quadrature of one of the modes is measured. The resulting state of the other mode exhibits Wigner function with negative regions (see Figure 2) and a characteristic crescent (or banana) shape. Using the analytical solution for the photon loss into the correlated reservoirs in the generation process as described above, partner USTAN has theoretically demonstrated, that even when the mean photon loss is 50% , the negative region of the Wigner function is still present. Now compare this with the situation when losses are introduced to the mode corresponding to the output non-Gaussian state after the lossless cross-Kerr interaction has taken place. Such losses are equivalent to mixing the mode with the vacuum state on a beam splitter (BS) and discarding one BS output. A 50% loss corresponds to a 50/50 BS. It is known that for such a balanced beamsplitter the Wigner function of one BS output can be expressed as a scaled Husimi Q-function of the input state and is clearly non-negative for all coherent state amplitudes, i.e., in the whole phase space of the mode. Therefore negative regions of the Wigner function cannot survive losses larger than 50% if these occur during propagation of the generated state. Hence losses that take place in the process of state generation via the cross-Kerr interaction are less harmful to the non-classicality of the output state than the same level of loss after the interaction.

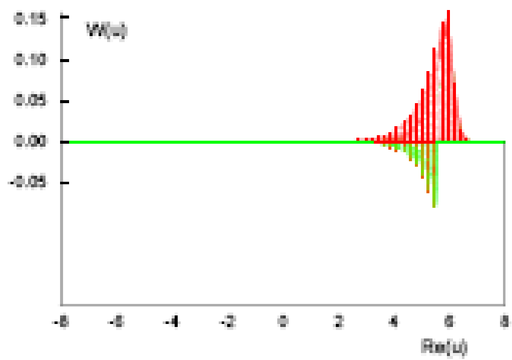


Fig. 2: *Highly non-Gaussian Wigner function exhibiting strong negative region for the output of the scheme based on the large cross-Kerr effect. Wigner function is viewed along the imaginary axis of the complex plane.*

Publications:

D. Mogilevtsev, T. Tyc, and N. Korolkova, *Influence of modal loss on the quantum state generation via cross-Kerr nonlinearity*, accepted in Phys. Rev. A, quant-ph ArXiv:0904.3235 (2009).

Reported progress towards Deliverable 2.4:
Experimental investigation of the cross-Kerr effect arising in an atomic vapour excited by short light pulses
(Partner CNRS/IO)

The goal of this work by partner CNRS/IO is to explore novel effects that may potentially be exploited in order to get a very high nonlinear effect. In particular, we are investigating the cross-Kerr effect that arises in an atomic vapour excited by short light pulses (a few ns). This approach may first provide squeezed light pulses, which may be transformed into non-Gaussian states by using measurement-induced nonlinear operations, as demonstrated in WP1.

For this purpose, we have built a pulsed homodyne detection working with nanosecond pulses at 780 nm, using the same principle as the one used in WP1, which uses femtosecond pulses at 850 nm. The non-linear effect will be then generated in a room-temperature cell containing Rubidium vapour, i.e. with $\chi^{(3)}$ (Kerr effect) non-linearity, rather than a $\chi^{(2)}$ (parametric) non-linearity. The main interest of this new approach is that both the wavelength and frequency bandwidth (inverse pulse duration) of the generated states will be well suited for atom-light interfaces.

At the present time, the new pulsed homodyne detection has been set up and characterized, and it is working properly. The first studies of the interaction between the light pulses and the atomic vapour have been carried out, and phase-dependant noise (above shot noise) has been observed. Experimental parameters are being optimized in order to obtain and characterize squeezed light pulses.

Task 2.4: Developing quantum networks based on CV quantum repeaters

Deliverable2.5: ***CV quantum repeaters based on complex quantum network geometries***

Status: Due month 24; Intermediate progress reported.

Partners: NBI, MPG

The objective is to assess the route towards the CV quantum repeater, exploiting quantum entanglement distillation, entanglement swapping, quantum memory, and complex quantum network geometries.

Reported progress towards Deliverable 2.5:
CV quantum repeater based on non-Gaussian 'Schrödinger cat' states
(Partner NBI)

A theoretical proposal for a new CV quantum repeater based on non-Gaussian, so called 'Schrödinger cat' states is being developed by partner NBI. We have demonstrated that using only homodyne detectors and linear optical components, near-deterministic entanglement swapping with such states is possible if one allows for a non-Gaussian local resource, with the efficiency of swapping set by the maximal photon number in the local resource states. Since homodyne detection can be very efficient, this implies that high achievable production rates for final entangled pairs can be reached with the CV repeater. In comparison, for repeaters based on Fock state-type entanglement, linear optics and single-photon detection, the efficiency of entanglement swapping is limited to a maximal value of 1/2 and is additionally suppressed by inefficient single-photon detectors. Furthermore, we have established how the necessary non-Gaussian states, both local and non-local, can be generated by means of homodyne detection and single-photon sources. In particular we have found a protocol for generating 'Schrödinger cat' states in an arbitrary number of modes. Currently, we are investigating the behavior of the CV repeater in the presence of noise, such as non-unit detection efficiency and imperfect single-photon generation, and the trade-off between fidelity and production time for the non-Gaussian states.

Reported progress towards Deliverable 2.5:
One-shot entanglement generation over long distances in noisy quantum networks
(Partner MPG)

The problem of creating a long-distance entangled state between two stations of a network, where neighboring nodes are connected by noisy quantum channels, was considered by partner MPG. It was shown that any two stations can share an entangled pair if the effective probability for the quantum errors is below a certain threshold, which is achieved by a local encoding of the qubits and a global bit-flip correction. In contrast to the conventional quantum-repeater schemes, there is no need to store the qubits in quantum memory for a long time: this protocol is a one-shot process (i.e., the elementary entangled pairs are used only once) involving one-way classical communication. Furthermore, the overhead of local resources increases only logarithmically with the size of the network, making this proposal favorable to long-distance quantum communication.

Publications:

S. Perseguers, L. Jiang, N. Schuch, F. Verstraete, M. D. Lukin, J. I. Cirac, and K. G. Vollbrecht, *One-shot entanglement generation over long distances in noisy quantum networks,* Phys. Rev. A **78**, 062324 (2008).

Workpackage 3: Demonstration of mesoscopic CV quantum processors

Period covered: from 01/04/08 to 31/03/09

Organisation name of lead contractor for this workpackage: DTU

Other contractors involved: FAU, USTAN, CNRS/IO, ULB, UP, MPG

Progress towards objectives of WP3 during year 1 of the project

A major progress has been achieved in the design of complex CV quantum information processors. In particular, advanced schemes for distillation of CV entanglement, CV quantum error correction, and CV quantum SUM gate have been successfully implemented. Also, two papers on experimental distillation of CV entanglement by COMPAS partners were published in Nature Physics.

Partners DTU, FAU and UP have demonstrated the mesoscopic distillation of deterministically prepared entangled light pulses that have undergone non-Gaussian noise. The pulses travelled through a lossy channel, where the transmission varied in time similarly to light propagation in the atmosphere. By employing linear optical components and global classical communication, the entanglement of the state was probabilistically increased. Partner UP realized, in collaboration with the group of Prof. R. Schnabel, the entanglement distillation and purification of phase-diffused two-mode squeezed states using interference on beam splitters and homodyne detection. In both experiments, the measurements clearly indicate a regained strength of entanglement and purity of the distilled states. The schemes achieved the actual preparation of the distilled states, which might therefore be used to improve the quality of downstream applications such as quantum teleportation.

Partners ULB and UP addressed CV quantum error correction, and established a no-go theorem precluding the existence of Gaussian error for Gaussian channels. Fortunately, it was also understood how this theorem may be circumvented in some interesting cases. In particular, partners DTU, FAU and ULB proposed and experimentally implemented a scheme fighting probabilistic erasures. A CV quantum erasure-correcting code was devised, which protects coherent states of light against erasures. Two different kinds of error correction were considered: deterministic correction where all states are actively displaced as a function of the syndrome outcomes, and a probabilistic correction where noise affected states are filtered out if an error was detected in the syndrome measurement. In an alternative approach to correct errors in CV quantum channels, partners FAU, DTU and UP proposed and experimentally demonstrated the non-destructive and noiseless removal (filtering) of vacuum states from an arbitrary set of coherent states of continuous variable systems. Errors, i.e., vacuum states in the quantum information are diagnosed through a weak measurement, and, on that basis, are probabilistically filtered out.

As a preliminary step towards the implementation of a teleportation-based quantum computer, partners DTU and FAU have implemented a high-efficiency quantum feed-forward loop for the execution of a new quantum cloning operation. The implemented transformation is optimised for the cloning of a pre-specified coherent state alphabet. A CV SUM gate solely based on off-line squeezed states, homodyne measurements, and feedforward has been demonstrated. The scheme was implemented in the group of Akira Furusawa at Tokyo University in collaboration with partners DTU and FAU. Finally, on the theory side, partners MPG, ULB, and CNRS/IO have made progress on a quantum version of de Finetti’s theorem for CV states, which should help our understanding of the special limiting role of Gaussian states in CV quantum information processing.

Task 3.1: Demonstrating CV one-way quantum computing and/or cat-state computing

Deliverable3.1: ***Cat states implementation of the sign-flip operation***
Status: Due month 36; No progress reported yet.

Deliverable3.2: ***Assessment of the implementation of the C-NOT and Hadamard gates***
Status: Due month 36, Intermediate progress reported

Partners: DTU, FAU

The first objective of this task is to pursue generation and utilization of squeezed and entangled states of light for teleportation-based implementation of quantum gates or for one-way CV quantum computing. A second research direction focuses on the experimental demonstration of quantum computing with cat states, including the realization of quantum gates (Hadamard and/or C-NOT gates) within this CV paradigm.

Reported progress towards Deliverable 3.2:
Experimental cloning of partial quantum information
(Partners DTU and FAU)

The efficiency of the teleportation based quantum computer crucially relies on the efficiency of the inherent quantum electro-optics feedforward system. Therefore, as a preliminary step towards the implementation of a teleportation-based quantum computer, partners DTU and FAU have implemented a high-efficiency quantum feed-forward loop for the execution of a new quantum cloning operation. The implemented transformation is optimised for the cloning of a pre-specified coherent state alphabet. We propose transformations that optimally (under the Gaussian assumption) clone symmetric Gaussian distributions of coherent states and as well as coherent states with known phases, and we implement experimentally a near-optimal transformation.

The implemented cloning transformation relies on simple linear optical components, homodyne detection and feedforward as shown schematically in figure 1. The signal a_{in} is reflected at a beam splitter with transmittance T_1 and detected using a beam splitter with transmittance T_2 and two homodyne detectors measuring amplitude x and phase p quadratures. The measurement outcomes are scaled with the gains g_x and g_p and used to displace the transmitted signal. The displaced state is subsequently split on a symmetric beam splitter, thus producing two clones.

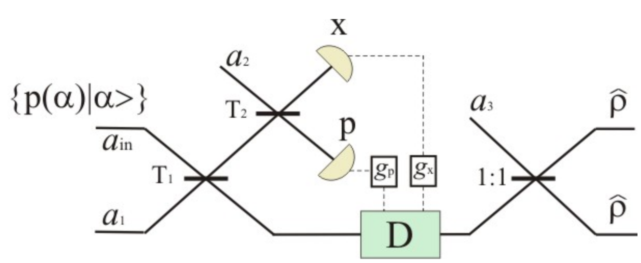


Fig. 1: *Schematic of the state dependent cloning setup.*

Making use of this machine we produced clones from two different alphabets and evaluated its performance quantitatively by the fidelity. For a symmetric Gaussian alphabet with variance 1.72 shot noise units, we measured a fidelity of F=77,5% which is very close to the optimal fidelity of F=78,5%. With an alphabet with known phases, we measured a fidelity F=89,0% which is close to maximally achievable with our setup (F=89,4%), and approaching the optimal of F=96,1% which can be achieved by using vacuum squeezed states as ancillas.

Publications:

M. Sabuncu, G. Leuchs and U.L. Andersen, *Experimental continuous variable cloning of partial quantum information*, Phys. Rev. A **78**, 052312 (2008).

Reported progress towards Deliverable 3.2:
Experimental demonstration of a CV SUM gate
(Partners DTU and FAU)

A crucial element in a CV cluster-state computer is the SUM gate, which is CV analog of discrete variable CNOT gate. The SUM gate is similar to a quantum non-demolition gate (or a two-mode entangling gate) and can be implemented with off-line squeezed vacuum states, linear optics and electro-optical feedforward. The scheme was implemented in the group of Akira Furusawa at Tokyo University, in collaboration with partners DTU and FAU.

The QND gate is characterized by the interaction Hamiltonian $H_{\text{int}} \propto x_1 p_2$, where the subscripts "1" and "2" denote two independent modes and the input-output relations in the Heisenberg picture are

$$x_{\text{out }1} = x_{\text{in}1} \qquad x_{\text{out}2} = x_{\text{in}2} + G\, x_{\text{in}1}$$
$$p_{\text{out}1} = p_{\text{in}1} - G\, p_{\text{in}2} \qquad p_{\text{out }2} = p_{\text{in }2},$$

where G is the interaction gain.

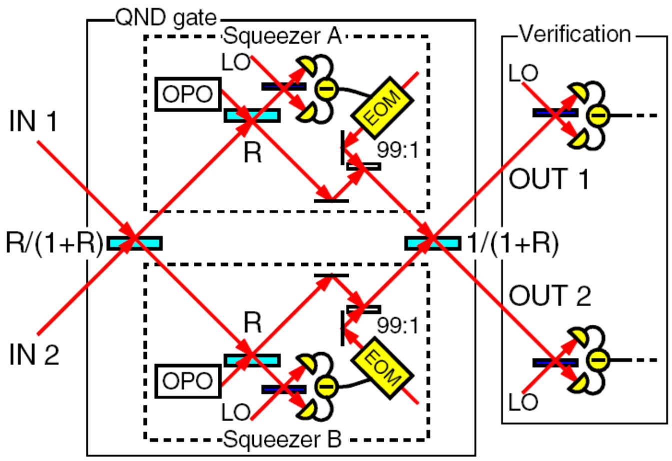


Fig. 1: *Schematic setup of the SUM gate.*

The QND gate is based on a Mach-Zehnder interferometer with a squeezer in each of the interferometer arms as shown in figure 1 above. The interaction gain G is determined by four variable beam splitters included in the experimental setup, two of them constructing the Mach-Zehnder interferometer and the other two determining the squeezing levels of the squeezers. As squeezers, we use teleportation-based squeezing gates which utilize offline resources of squeezed vacuum states, balanced homodyne measurements, and feed-forward. Each squeezed vacuum is generated by a sub-threshold optical parametric oscillator (OPO), which is composed of a bow-tie shaped cavity and a periodically-poled $KTiOPO_4$ crystal as a nonlinear optical medium. One advantage of the teleportation based squeezers is that they allow good control of the squeezing levels which simply relies on the reflectivity (R) of the beam splitter, and an appropriate feed-forward gain (although limited by the finite squeezing of the OPOs).

To quantify the performance of the SUM, gate we used the standard measures for QND interaction, namely the transfer coefficient for the signal (T_s) and the meter (T_m) as well as the conditional variance Vs|p. The usual criteria for QND interaction are $1<T_s+T_p<2$ and Vs|p<1. The transfer coefficients are estimated by measuring the first and second moments of the input and output state, and we measured (for unity gain, G=1) $T_s+T_p=1.20$ and $T_s+T_p=1.10$ for the amplitude and phase quadrature, respectively. Measurements that lead to the estimation of the conditional variance are depicted in figure 2. Here we plot the noise correlations between the output quadratures as a function of the gain g. The minima (of the blue curve) correspond to the conditional variance, and we find that Vs|p=0.75 for the amplitude quadrature and Vs|p=0.78 for the phase quadrature.

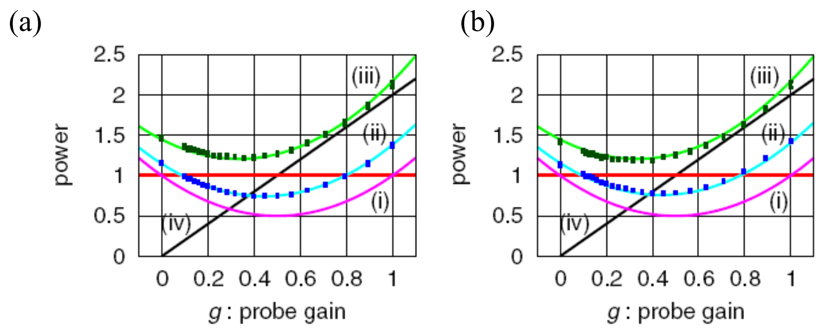


Fig. 2: *Variances of (a) $x_{out\,1}$ - g $x_{out\,2}$ and of (b) $p_{out\,2}$ - g $p_{out\,1}$: (i) theoretical prediction for an ideal QND interaction, (ii) a QND interaction with finite degrees of squeezing of the ancilla modes, (iii) and with vacuum ancilla modes. By entering the areas below the lines (iv) entanglement is verified.*

Publications:

J. Yoshikawa, Y. Miwa, A. Huck, U. L. Andersen, P. v. Loock, and A. Furusawa, *Experimental Demonstration of a Quantum Nondemolition Gate*, Phys. Rev. Lett. **101**, 250501 (2008).

Y. Miwa, J. Yoshikawa, A. Huck, U. L. Andersen, P. v. Loock, and A. Furusawa, *Experimental Demonstration of a Quantum Nondemolition Gate*, QCMC Proceedings (2008).

Presentations:

Poster presentation at '*Quantum Communication, Measurement and Computing*' (QCMC) 2008, University of Calgary/Canada.

<u>Task 3.2</u>: Demonstrating CV quantum error correction

Deliverable3.3: ***Demonstration of CV quantum error correction***

Status: Due month 24; Intermediate progress reported.

Partners: DTU, FAU, ULB, and UP

The goal of this task is to develop quantum protocols for the correction (or detection) of errors (or erasures) that are suitable to CV information carriers. These protocols, in which information is encoded into a CV multipartite entangled mesoscopic state, should be useful for circumventing the noise in distributed quantum computing networks.

Reported progress towards Deliverable 3.3:
Experimental demonstration of CV quantum error correction protecting against erasures
(Partners DTU, FAU, and ULB)

Quantum information processing relies on the robust and faithful transmission, storage and manipulation of quantum information. However, since errors are inherent to any realistic implementation, the future of quantum information systems strongly relies on the ability to detect and correct for these errors.

We have proposed and experimentally implemented a scheme for combating erasure errors in a continuous variable (CV) quantum channel. More specifically, we have devised a CV quantum erasure-correcting code, which protects coherent states of light against complete erasure. As shown in figure 1, the scheme encodes two coherent states into a bi-partite entangled state, thus resulting in a four-mode erasure code. The two ancillary squeezed vacuum states are produced in two optical parametric oscillators and the coherent state is generated at a 5.5MHz sideband employing amplitude and phase modulators. Subsequently, the four-mode code is launched into four free-space channels that independently and randomly erase the conveyed beams.

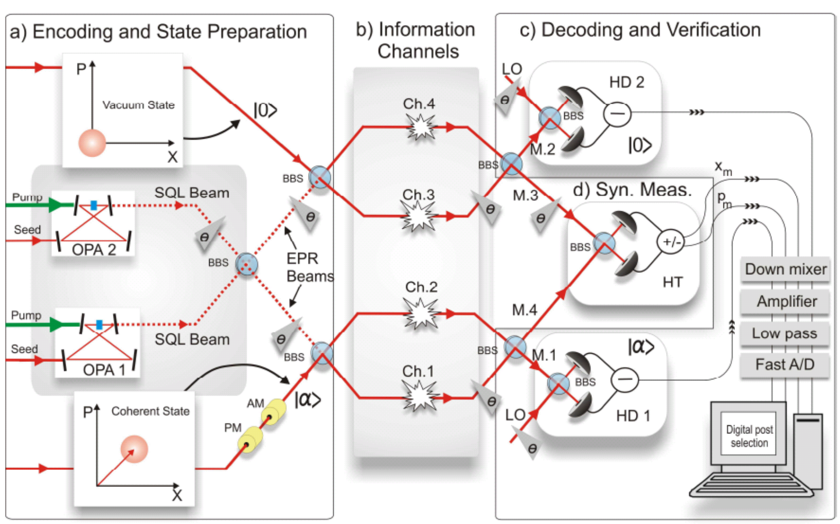


Fig. 1: *Schematic setup of the quantum erasure correcting code.*

After transmission, the receiving beams are brought to interference as shown in the figure and the error is subsequently probed in a syndrome measurement where conjugate quadratures are detected. Errors in the remaining beams are then corrected based on the outcome of the syndrome measurements. We have been investigating two different kinds of error correction: Deterministic correction where all states are actively displaced as a function of the syndrome outcomes, and a probabilistic correction where noise affected states are filtered out if an error was detected in the syndrome measurement. The former approach only allows for a single error (at the time) and the location of the error must be a priori know, whereas the latter approach allows for multiple erasures and ignorance about the location of the erasures.

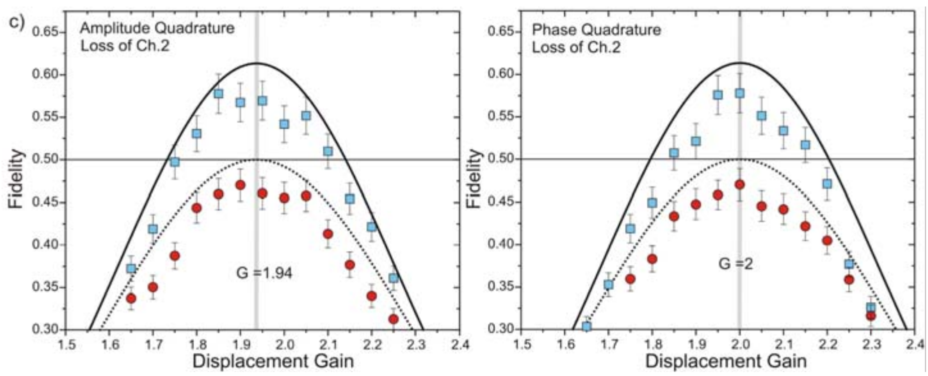


Fig. 2: *Protocol fidelity as a function of the displacement gain for deterministic quantum erasure correcting coding.*

The protocol is quantified in terms of the transmission fidelity and the results for the deterministic and probabilistic protocols are shown in figures 2 and 3, respectively. In figure 2, the fidelity is plotted as a function of the displacement gain both for the entanglement based error code (blue squares) and without entanglement. We find maximum fidelities of 58% which clearly surpasses the classical benchmark of 50%.

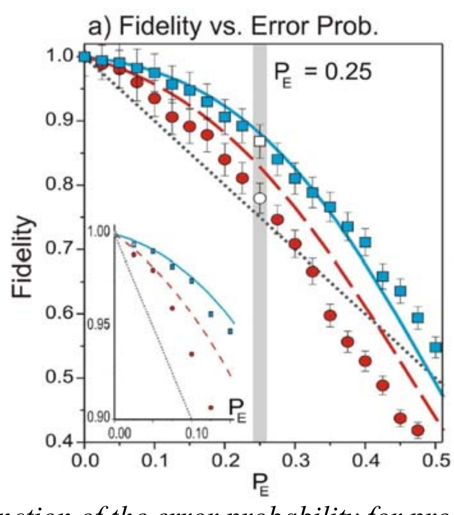


Fig. 3: *Protocol fidelity as a function of the error probability for probabilistic recovery of quantum information.*

For the probabilistic error code we show experimentally that the transmitted state can be corrected by selecting these states for which syndrome measurement outcomes obeyed $|x_m| < 0.8$ and $|p_m| < 0.8$. Other states were discarded. For an error probability of $P_E=0.25$ we compute a transmission fidelity of $F = 0.87 \pm 0.02$, which clearly surpasses the transmission fidelity of F=0.75 obtained by transmission in a single channel with similar erasure probability. The fidelities for different error probabilities were computed based on the measurements and the results are shown in figure 3 for the entanglement based code (blue squares) and the entanglement-free code (red circles). The dotted line is the fidelities associated with a single channel transmission, and we clearly see that the erasure code is superior for a large range of error probabilities.

Publications:

J. Niset, U.L. Andersen and N.J. Cerf, *Experimentally Feasible Quantum Erasure Correcting Code for Continuous Variables*, Phys. Rev. Lett. **101**, 130503 (2008).

M. Lassen, M. Sabuncu, A. Huck, J. Niset, G. Leuchs, N.J. Cerf and U.L. Andersen, *Experimental quantum erasure correction for continuous variables* , submitted.

Presentations:

U.L. Andersen, R. Dong, R. Filip, J. Niset, N. Cerf, M. Lassen and G. Leuchs, *Combating erasure noise – entanglement distillation and and correction coding*, The 17th International Laser Physics Workshop (LPHYS'08), June 30- July 4, 2008, Trondheim, Norway. [INVITED TALK]

U. L. Andersen, N.J. Cerf, M. Lassen, G. Leuchs, J. Niset, and M. Sabuncu, *Quantum error correction coding with continuous variables*, The 18th International Laser Physics Workshop (LPHYS'09), July 13- July 17, 2009, Barcelona, Spain. [INVITED TALK]

M. Lassen, M. Sabuncu, A. Huck, J. Niset, G. Leuchs, N.J. Cerf and U.L. Andersen, *Continuous Variables Quantum Erasure-Correcting Code*, International Conference of Squeezed States and Uncertainty Relations (ICSSUR'2009), Olomouc, Czech Republic, June 22 – 26, 2009. [INVITED TALK].

Reported progress towards Deliverable 3.3:
A No-Go Theorem for Gaussian Quantum Error Correction
(Partners ULB and UP)

Given the present state of CV quantum information technologies, understanding what is possible or not within the Gaussian regime is of a great importance as it underpins the "main stream" use of optical continuous variables in quantum information protocols. The set of Gaussian states and operations are indeed known to enable many quantum information primitives, such as quantum teleportation, quantum key distribution, and quantum cloning. In the case of photonic CV quantum information carriers, the entire set of Gaussian operations can be implemented by combining passive linear optical components such as beam splitters and phase shifters together with squeezers and homodyne detection followed by feed-forward. All these elements are, up to some degree, readily accessible in today's optical laboratories.

However, manipulating Gaussian states with Gaussian operations also leads to some limitations. Probably the most significant one is the impossibility to distill entanglement from Gaussian entangled states with Gaussian local operations and classical communication {1,2,3}. As a result, some important quantum primitives, such as quantum repeaters, cannot be implemented within the Gaussian regime and hence require the use of experimentally more demanding non-Gaussian resources, such as photon subtraction.

In the framework of COMPAS and its precursor project COVAQIAL, several schemes have been developed to fight noise and losses in continuous-variable quantum transmission lines. Given the well-known connection between quantum error correction and entanglement distillation for discrete-variable quantum systems, the existence of a no-go theorem for Gaussian error correction was suspected, but had yet remained unresolved. Partners ULB and UP have addressed this problem and have proven that Gaussian operations are of no use for protecting Gaussian states against Gaussian errors in quantum communication protocols. Specifically, a new intrinsic parameter of single-mode Gaussian channels was introduced, called *entanglement degradation*. This parameter characterizes the extent to which the channel degrades entanglement when acting on one half of an entangled state at the limit of infinite squeezing. Then, by exploiting the connection between quantum error correction and entanglement distillation in the Gaussian regime, it was shown that the *entanglement degradation* cannot decrease via Gaussian encoding and decoding operations only. This no-go theorem definitively establishes the impossibility of improving the transmission of Gaussian states in a Gaussian channel with Gaussian error correction only.

References:

{1} J. Eisert, S. Scheel, and M.B. Plenio, Phys. Rev. Lett. **89**, 137903 (2002).
{2} J. Fiurasek, Phys. Rev. Lett. **89**, 137904 (2002).
{3} G. Giedke, and J.I. Cirac, Phys. Rev. A **66**, 032316 (2002).

Publications:

J. Niset, J. Fiurasek, and N.J. Cerf, *A No-Go Theorem for Gaussian Quantum Error Correction*, Phys.Rev.Lett. **102**,120501 (2009).

Conference presentations:

N.J. Cerf, *Continuous-variable quantum error correction: possibilities and impossibilities*, NEC America, Research Labs, Princeton, USA, December 1st, 2008. [INVITED SEMINAR]

N.J. Cerf, *Continuous-variable quantum error correction: possibilities and impossibilities*, Center for Theoretical Physics, Massachusetts Institute of Technology, Boston, USA, December 8, 2008. [INVITED SEMINAR]

N.J. Cerf, *Continuous-variable quantum error correction: possibilities and impossibilities* Quantum Information Science Series, Science Development Program, BBN Technologies, Cambridge, USA, January 9, 2009. [INVITED SEMINAR]

Task 3.3: Demonstrating quantum noise filtering in CV systems

Deliverable 3.4: ***Filtering of noise in CV systems***

Status: Due month 24; Delivered in advance; Additional unexpected progress reported.

Partners: FAU, DTU, UP, MPG, ULB, CNRS/IO

The goal of this task is to develop and demonstrate protocols for filtering the noise that is superimposed on CV quantum states. The filtering can be based, e.g., on photon counting measurements, and conditioning on the measurement outcomes. Such filtering techniques could suppress discrete noise arising, e.g., due to timing-jitter or beam positioning fluctuations. Such noise is likely to be present in any implementation of advanced CV quantum information processing schemes. Additional results, which are related, though to a smaller extend, to noise filtering are also reported here. In particular, extensions of de Finetti's theorem to the CV paradigm provides a way to approach the resistance to noise of CV quantum key distribution.

Reported progress towards Deliverable 3.4:
Experimental demonstration of Filtering of non-Gaussian Noise from Continuous-Variable Quantum Information
(Partners FAU, DTU and UP)

Quantum communication employing coherent state encoding and quadrature detection is an interesting alternative to the commonly used single-photon strategy. As an example, information can be encoded into binary coherent states (e.g. $|\alpha\rangle$ and $|-\alpha\rangle$) and measured using either homodyne or heterodyne detectors. Any communication link is however inflicted by noise. Therefore, in order to remove noise from the signal, a filter protocol is needed. Partners FAU, DTU, and UP have implemented the process of filtering non-Gaussian noise from binary coherent states using two different measurement methods: homodyne detection and on/off detection.

(a) (b)

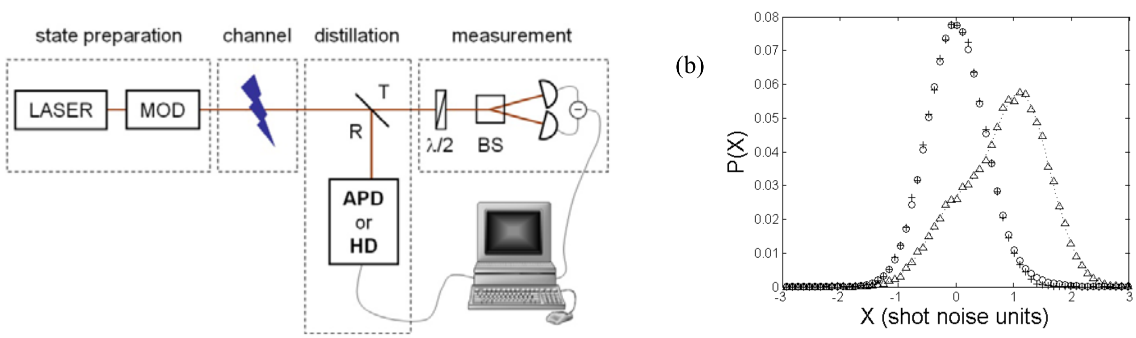


Fig. 1 *(a) Experimental Setup; MOD–amplitude or phase modulator, BS-beam splitter, APD-avalanche photo diode, HD-homodyne detection. (b) Marginal distributions illustrate the improvement of signal quality (crosses show the vacuum state, circles and triangles show the state without and with filter (in this case APD-filter).*

Let us consider a coherent state ($|\alpha\rangle$ or $|-\alpha\rangle$) transmitted through a channel with inherent random losses; it is preserved with the probability p or replaced by a vacuum state with the probability 1−p. Physical examples are an extreme time jitter channel or a channel which is randomly blocked due to e.g. atmospheric disturbances. The idea of filtering is then to increase the probability p by removing the vacuum contribution in a noiseless way. A schematic of the experimental setup is shown in Fig. 1(a). The prepared noisy state is incident upon an asymmetric beam splitter, and the reflected part is estimated using two different measurement techniques; either an avalanche photo diode in the breakdown mode or a homodyne detector. The homodyne detector is set to measure the quadrature along which the coherent state is displaced. Therefore, in the tapped signal the goal is to discriminate the coherent states from vacuum. Conditioned on these measurements, the signal is selected only if the detection output lies outside a certain interval (for the homodyne detection) or if the detector fires (for the on/off detector). Such a scheme enables a probabilistic filtering.

Characteristics of homodyne and on/off detection in such a filter are compared and the optimal device is discussed. The performance of the protocol was characterized by measuring the signal state probability before and after filtration as shown in Fig. 1(b). We also measured the success probability (that is, the probability for a positive filter output) as well as the filter sensitivity for extremely weak signal states.

Publications:
C. Wittmann, D. Elser, U. L. Andersen, R. Filip, P. Marek,and G. Leuchs, *Quantum filtering of optical coherent states*, Phys. Rev. A **78**, 032315 (2008).

Reported progress towards Deliverable 3.4: (Unexpected extra progress)
Extension of de Finetti's theorem to infinite dimensional systems
(Partner MPG)

The de Finetti theorem has various applications in the context of quantum information processing where it is often hard to bound the dimension of information carriers (which may be corrupted by an adversary). In this work, de Finetti's theorem is extended, showing that it also holds for infinite dimensional systems, as long as the state satisfies certain experimentally verifiable conditions. In particular, this result can be applied to calculate the level of noise for which quantum key distribution schemes based on weak coherent states or Gaussian states can be considered secure against general attacks.

Publications:
R. Renner and J.I. Cirac, *A de Finetti representation theorem for infinite dimensional quantum systems and applications to quantum cryptography*, Phys. Rev. Lett. **102**, 110504 (2009).

Reported progress towards Deliverable 3.4: (Unexpected extra progress)
Quantum de Finetti's theorem in phase space
(Partners ULB and CNRS/IO)

Gaussian states are well known to play a pivotal role in CV quantum information. Some protocols can be implemented with Gaussian states, such as quantum teleportation, quantum cloning, or quantum key distribution, whereas others cannot, e.g., quantum entanglement purification, quantum error correction, or quantum computing. In addition, it is known that Gaussian states make a spetial class of CV states given their extremality properties. For example, among all CV states with a given covariance matrix, Gaussian states are the more disordered ones (those with the highest von Neumann entropy).

A main objective of COMPAS is to better understand this special role of Gaussian states, in particular, the convergence towards Gaussian states in specific situations. The de Finetti theorem is an appropriate framework to investigate this convergence. In a classical setting, the de Finetti theorem addresses the statistics of large composite systems obeying some fundamental symmetry (e.g., invariance under permutations of its parts), stating that its parts can be well approximated by identical independent subsystems. In the language of probability theory, a permutation-invariant joint probability distribution of n random variables is shown to approach a probabilistic mixture of *independent and identically distributed* (i.i.d.) variables. In a quantum setting, the theorem makes the connection between symmetric states, i.e., states that are invariant under permutations of their n subsystems, and probabilistic mixtures of i.i.d. (product) states. According to the (standard) quantum de Finetti's theorem {1,2}, a symmetric state becomes increasingly close to a mixture of i.i.d. states as one traces out more of its parts.

Attempts at characterizing the speed of this convergence towards an i.i.d. state express the trace distance between the partial trace over (n-k) parties of an n-partite symmetric state and a mixture of k-partite i.i.d. states. Interestingly, a striking difference with the classical case is that the trace distance in the quantum case necessarily depends on the dimension d of the Hilbert space (the trace distance is bounded from above by $2\ d^2\ k/n$), which rules out the possibility of a direct generalization of the theorem to an infinite-dimensional Hilbert space. A possible approach, followed by partner MPG (see above) consists in applying a truncation to the Hilbert space and controlling the effect of this truncation.

Partners ULB and CNRS/IO have revisited this problem by following a radically different approach, considering a symmetry group different from the permutation group. The idea is to focus on *orthogonally-invariant* states, that is, states that are invariant under the action of any n-mode Gaussian unitary operator corresponding to a real symplectic orthogonal transformation in the associated $2n$-dimensional phase. This leads to a new type of quantum de Finetti's theorem, which is particularly relevant to continuous-variable systems. Specifically, an n-mode bosonic state that is invariant with respect to this continuous symmetry in phase space is proven to converge towards a probabilistic mixture of i.i.d. Gaussian states (actually, n identical thermal states). This gives another special role to Gaussian CV states.

References:

{1} R. Hudson and G. Moody, Probability Theory and Related Fields **33**, 343 (1976).
{2} C. Caves, C. Fuchs, and R. Schack, Journal of Mathematical Physics **43**, 4537 (2002).

Publications:

A. Leverrier, E. Karpov, P. Grangier, and N.J. Cerf, *Security of continuous-variable quantum key distribution: exploiting symmetries in phase space*, submitted to New Journal of Physics, (February 2009).

A. Leverrier and N.J. Cerf, *A quantum de Finetti theorem in phase space representation*, submitted to Phys. Rev. A; arXiv:0904.4862 [quant-ph].

Reported progress towards Deliverable 3.4: (Unexpected extra progress)
Correlation measurement of squeezed light
(Partners FAU and DTU)

In optics experiments one converts light energy into electrical fluxes by means of photo-detectors which provide reliable information about the intensity of the light source. However, in some cases the characterisation of the source is not always limited by observations of its intensity and might require some more elaborate analysis. Indeed, such kind of "peculiar" sources and their characterisation are among the major interests of modern quantum optics. For example, a considerable interest is attracted by light consisting of pairs of correlated photons, generated in non-linear optical processes. In designing the detection system for such a source one substitutes the single photo-detector with two photo-detectors whose outputs are correlated by high resolution electronics. Thus, observation of coincidences of two electronic pulses captures the presence of tightly correlated photon pairs.

Partners FAU and DTU aimed to determine the potential of correlation techniques within the CV quantum optics environment. Surprisingly, it turns out, that correlation measurements can advance traditional approaches being more robust to technical noise while still remaining quite informative. In many experiments one deals with generation and manipulation of squeezed states of light. The conventional method to characterise squeezed light is balanced homodyne detection, where the state under investigation (often a squeezed state) is mixed on a symmetric beam splitter with a local oscillator (LO) and the difference photocurrent of two analog photo-detectors is recorded.

In the present work we apply the correlation technique for characterization of squeezed light and compare its performance to standard homodyne detection. In our work we consider two different sources of squeezed light. One is based on the Kerr nonlinearity in an optical fiber and another is based on parametric down-conversion in an optical cavity. The general idea is to analyze the time resolved data from two detectors and to calculate the covariance coefficient of the photocurrent. The main conclusions drawn from our experiments are the following:

(1) The sign of the covariance coefficient unambiguously defines noise suppression of a certain quadrature, chosen by the phase of the LO. Thus, from the correlation data we are able to distinguish: squeezed states, coherent states and a state with excess classical noise.

(2) The role of uncorrelated electronic noise of the detector is minimized by using the correlation approach as opposed to homodyning where it often becomes a crucial issue. This allows us to make much more accurate determination of the degree of squeezing at the regime where the power of the LO is very low and contributions of the electronic noise of the detectors become significant.

From the conclusions above it follows that correlation measurements provide a powerful tool in a wide range of experiments with squeezed light, especially where the uncorrelated noise contribution strongly affects the measurements results.

Publications:

L.A. Krivitsky, U.L. Andersen, R. Dong, A. Huck,C.Wittmann,and G. Leuchs, *Correlation measurement of squeezed light*, Phys. Rev. A 79, 033828 (2009).

L. A. Krivitsky, U. L. Andersen, R. Dong, A. Huck, C. Wittmann, and G. Leuchs, *Electronic noise-free measurements of squeezed light*, Opt. Lett. **33**, 2395-2397 (2009).

Conference presentations:

L.A. Krivitsky, *Correlation measurement of Squeezed Light*, Danish Optical Society meeting, Nyborg, Denmark, 17-18 June, 2008.

L.A. Krivitsky , *Correlation measurement of Squeezed Light*, International conference on Laser Physics "Lasphys08" Trondheim, Norway, 30June- 4 July, 2008.

Task 3.4: Demonstrating the distillation and/or concentration of CV entanglement

Deliverable 3.5: ***Distillation or concentration of CV entanglement***

Status: Due month 36; Delivered in advance; Additional unexpected progress reported.

Partners: FAU, DTU, UP, USTAN, ULB

The distribution of entangled quantum states of light over long distances is a major challenge in the field of quantum information. Optical losses, phase diffusion and mixing with thermal states lead to decoherence and destroy the nonclassical states after some finite transmission line length. This problem can be overcome by quantum repeaters combining quantum memory, entanglement swapping and entanglement distillation. The objective of this task is to develop the various ingredients needed to demonstrate entanglement distillation and/or concentration, on the way to the CV quantum repeater. Related theoretical issues, such as the capacity of CV quantum channels, are also reported here.

Reported progress towards Deliverable 3.5:
Experimental demonstration of continuous variable entanglement distillation of non-Gaussian states from a single copy
(Partners DTU, FAU and UP)

One of the main tasks of quantum information and communication is to transmit quantum information between distant sites. From this aspect, non-classical states, for example, continuous variable entangled states are an invaluable carrier to many continuous variable (CV) quantum information protocols such as quantum teleportation and quantum dense coding. Therefore, the success of such protocols depends strongly on the degree of the entanglement of the carrier state. However, such entangled states are very sensitive to the unavoidable and devastating interaction with the environment. For instance, for satellite communication, the free-space atmosphere channel exhibits a wide variety of deleterious effects such as non-stationary attenuation etc. This fluctuation of the attenuation factor results in non-Gaussian noise, and the phenomena is known as fading. Such interaction will corrupt the entanglement if one party of the entangled state transmit through such channel and destroy the information. Fortunately, due to the non-Gaussian character of the noise, it is possible to recover the corrupted entanglement by simply tapping off a small portion of the loss afflicted beam and applying post-selection techniques.

Partners DTU, FAU, and UP demonstrated the first successful experiment for distilling entanglement from single copies of states that have undergone attenuation in a lossy channel with a varying transmission. The schematic setup is shown in Fig. 1. We prepare the entangled state by using two efficient, fiber-based polarization squeezers and interfering the two output polarization squeezed states on a 50:50 beam splitter, then we get polarization entangled state as the input of a certain fading channel. In the experiment, the entanglement is demolished due to one party of the entangled beams passing through a fading channel, which is implemented by a circular variable neutral density filter inserted into the beam. We accomplish two steps of measurements: To implement the distillation, we tap off a small portion (7%) of the attenuated beam and apply homodyne detection on the tapped beam. The outcomes will be used as the basis for the post-selection of the data measured in the verification step, allowing us to regain the non-classical input state with certain probability. The verification measurement is made by doing the joint measurement on the corrupted entangled beams, and a measure of log-negativity of the state is adopted to demonstrate the quality of the entanglement. As we require the full photon statistics, the detector signals are down-mixed, amplified and then sampled to a digital signal.

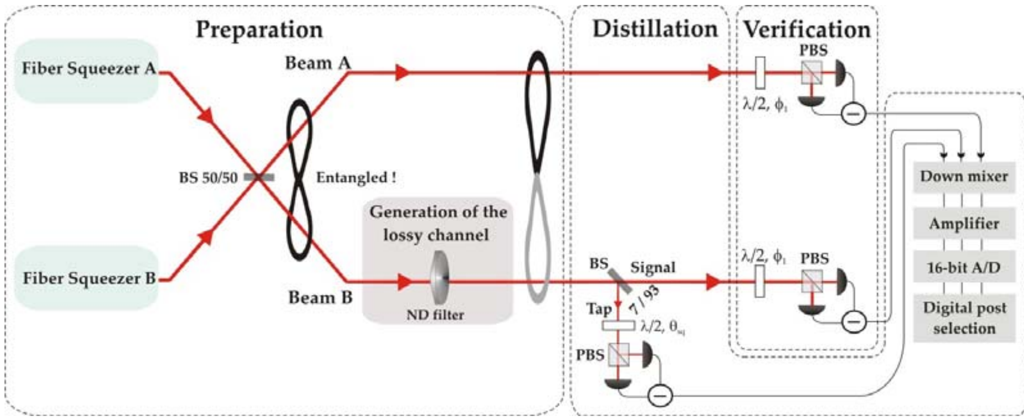


Fig. 1: *Schematic of the experimental setup for the generation, distillation and verification of the distillation of non-Gaussian entangled states.*

As a simple example of the entanglement distillation, we first depict the experimental results for a discrete fading channel, a 50/50 mixture of attenuation levels 0% and 75%. After transmission through such a channel the resulting state is a mixture of a highly entangled state and a weakly entangled state. The statistics of beam B is contaminated with the attenuated entangled state thus producing non-Gaussian statistics. For this state we find that the Gaussian entanglement is completely lost as a result of the introduction of such time-dependent loss (the Gaussian logarithmic negativity (LN) is measured to be -1.63±0.02 < 0). Implementing entanglement distillation, the Gaussian LN has been computed for several choices of the threshold value X_{th}, and is plotted in Fig. 2 as a function of the associated success probabilities by black open circles. The probability distributions of the two superimposed states in the mixture after distillation are also shown for different post-selection thresholds, which corresponds to X_{th} = 0.0, 2.0, 4.0, 6.0, 9.0, labeled by 1-5, respectively. We see that, as the threshold increases, the Gaussian LN increases, ultimately approaching the LN of the input entanglement and the probability distribution tends to a single valued distribution, therefore the mixture of two Gaussian entangled states reduces to a single highly entangled Gaussian state, thus demonstrating the act of Gaussification. Based on the experimental parameters, the theoretical simulation is plotted by red curve and it shows a very good agreement with the experimental results. To show that the total entanglement of the state has increased as a result of distillation, we compute an upper bound for the LN before distillation. Surpassing this bound after distillation tells that the state is Gaussified. The upper bound of LN without the Gaussian approximation is computable from the LN of each Gaussian state in the mixture and we find LN_{upper} = 0.49, which is shown in Fig. 2 by the dashed black line. We see that for a success probability around 10^{-4} the Gaussian LN crosses the upper bound for entanglement, and since the state at this point is perfectly Gaussified we may conclude that the total entanglement of the state has increased as a result of the distillation protocol. Fig. 2-5 gives the explicit explanation by showing that the probability contribution from the 75% attenuated data reaches 0 when the post selection threshold is set to X_{th} = 9.0, this corresponds to the distilled entanglement of LN^{dist} = 0.67±0.08 with a success probability $P_S = 1.69\times10^{-5}$. However, from Fig. 2-3 and 2-4, we see that even a small contribution from the 75% attenuated data will submerge the useful entanglement for Gaussian operations.

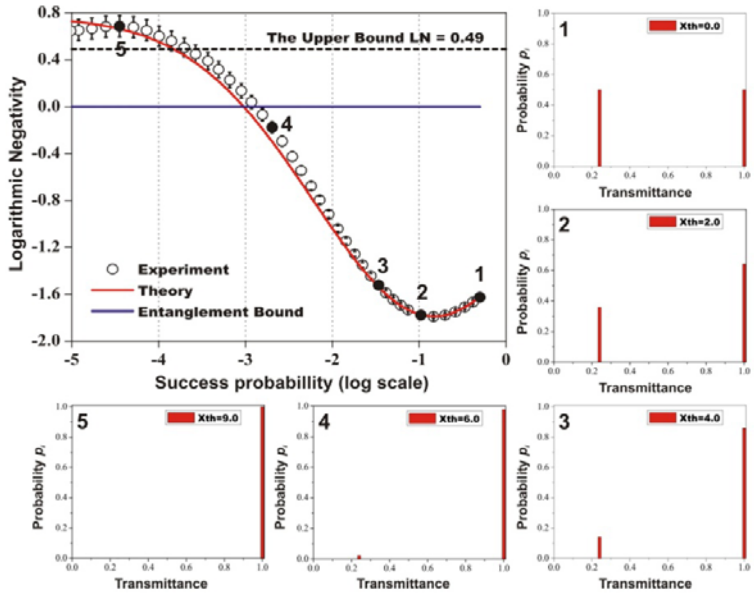


Fig. 2: *Experimental results for distillation of an entangle state transmitted through a discrete lossy channel. The experimental results are marked by circles and the theoretical prediction is plotted by the red solid line. The bound for Gaussian entanglement is given by the blue line, and the upper bound for total entanglement before distillation is given by the black dashed line. The weight of the two constituents in the mixed state after distillation for various threshold values is also experimentally investigated and shown in the plots labelled by 1-5.*

Furthermore, this protocol is successfully demonstrated for a semi-continuous transmission channel which simulates a free-space optical communications channel where atmospheric turbulence causes scattering and beam pointing noise. After propagation through this channel the Gaussian LN of the mixed state is found to be −0.11±0.05. The state is subsequently distilled and the Gaussian LN is increased as the threshold value increases (and the success probability decreases), ultimately reaching $LN^{dist} = 0.39 \pm 0.07$ with a success probability $P_S = 1.66\times10^{-5}$. The demonstration of this distillation protocol provides a crucial step towards the construction of a quantum repeater for transmitting continuous variables quantum states over long distances in channels inflicted by non-Gaussian noise.

Publications:

R. Dong, M. Lassen, J. Heersink, C. Marquardt, R. Filip, G. Leuchs, and U. L. Andersen, *Experimental entanglement distillation of mesoscopic quantum states*, Nature Phys. **4**, 919 - 923 (2008).

Conference presentations:

R. F. Dong, M. Lassen, J. Heersink, C. Marquardt, R. Filip, U. L. Andersen, G. Leuchs, *Experimental Demonstration of Continuous Variable Entanglement Distillation* (accepted)", 11th International Conference on Squeezed States and Uncertainty Relations (ICSSUR) June22-26, 2009 in Olomouc, Czech Republic. [INVITED TALK]

M. Lassen, R. F. Dong, J. Heersink, C. Marquardt, R. Filip, U. L. Andersen, G. Leuchs, *Continuous Variable Entanglement Distillation of Non-Gaussian States*, The ninth international Conference on Quantum Communication, Measurement and Computing (QCMC) August 19-24, 2008 in Calgary, Canada. [POSTER]

R. F. Dong, M. Lassen, C. Marquardt, R. Filip, U. L. Andersen, G. Leuchs, *Experimental Demonstration of Continuous Variable Entanglement Distillation*, CLEO/QELS May 4-9, 2008 in San Jose, California, USA. [INVITED TALK]

R. F. Dong, M. Lassen, C. Marquardt, R. Filip, U. L. Andersen, G. Leuchs, *Distillation of entangled state after a fading channel*, DPG Spring Meeting March 10-14, 2008 in Darmstadt, Germany. [TALK]

Reported progress towards Deliverable 3.5:
Experimental entanglement distillation of phase-diffused two-mode squeezed states
(Partner UP)

Partner UP, together with the experimental group of Prof. R. Schanbel in Hannover, demonstrated the first experimental distillation of entanglement from two copies of a noisy entangled state in the continuous variable regime. Entangled squeezed states were first disturbed by random phase fluctuations and then distilled and purified using interference on beam splitters and homodyne detection. Measurements of covariance matrices clearly indicated a regained strength of entanglement and purity of the distilled state. An important feautre of the protocol is that it achieves the actual preparation of the distilled states, which might therefore be used to improve the quality of down-stream applications such as quantum teleportation.

The experimental setup is shown in Fig. 1. Two optical parametric amplifiers (OPAs) provided two continuous wave light fields that carried squeezed states of light. Both squeezed states were mixed with vacuum states on balanced beam splitters in order to prepare entangled states. All four resulting beams were transmitted to two stations A and B through four channels exhibiting independent phase noise. The noisy channels were realized by quasi-random electro-mechanical actuation of mirror positions in the beam paths in order to mimic the phase noise introduced for example in optical fibres. The phase diffusion transforms the originally Gaussian squeezed states into non-Gaussian states that can be distilled by Gaussian operations. Each station A nad B receives one mode from each copy of the state. These two modes are combined on a balanced beam splitter and one output port on each side is measured by a homodyne detector producing outcomes $X_{T,A}$ and $X_{T,B}$, respectively. The trigger condition determining the success of the distillation protocol is given by $|X_{T,A}+X_{T,B}|<Q$, where Q was a certain threshold whose value could be tuned in order to vary the selectivity of the protocol. The results are shown in right panel of Fig. 3.5.3. The distillation reduces the value of the EPR variance of the two-mode state which is a clear signature of reduced noise and increased entanglement of the state.

The protocol provides two open ports that output the distilled entangled states, and is therefore unconditionally useful for arbitrary down-stream quantum information applications. The reported entanglement distillation, purification and Gaussification protocol can be iterated and combined with already experimentally demonstrated single-photon subtraction to implement a fully universal CV entanglement distillation protocol.

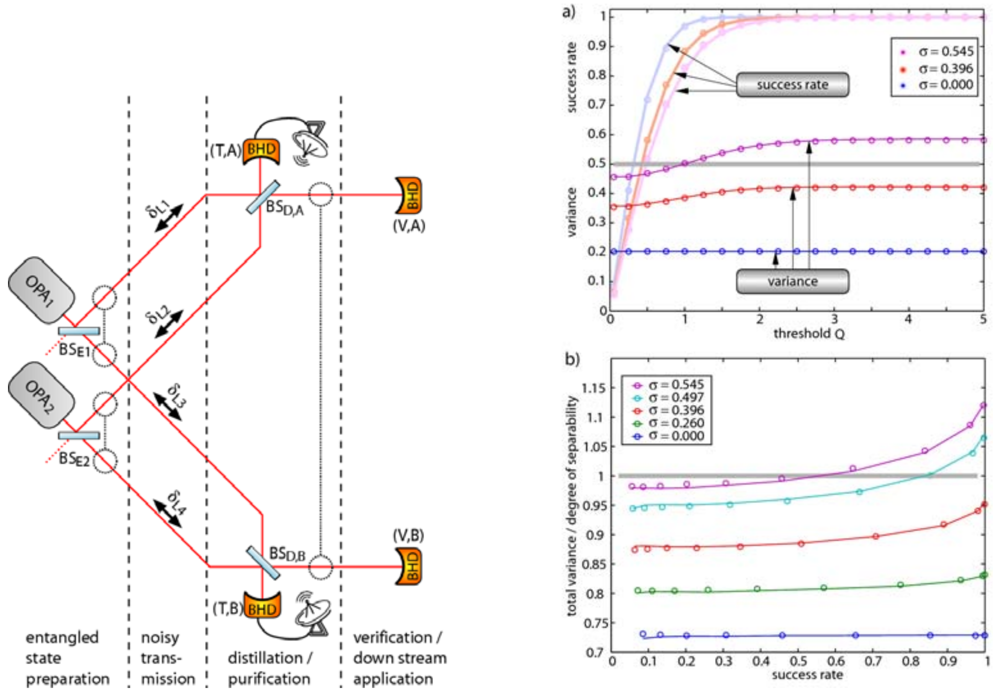


Fig. 1: *Left panel – Experimental setup. Right panel - (a) Variance of $X_{V,A}+X_{V,B}$ and corresponding success rates versus threshold value Q for different strengths of the phase fluctuations. (b) The EPR variance I is plotted against the success rate. Symbols represent experimental data and lines correspondiong numerical simulations.*

Publications:

B. Hage, A. Samblowski, J. DiGuglielmo, A. Franzen, J. Fiurášek, and R. Schnabel, *Preparation of distilled and purified continuous-variable entangled states*, Nature Phys. **4**, 915 (2008).

Reported progress towards Deliverable 3.5: (Unexpected extra progress)
Weak measurements for noiseless amplification and entanglement distillation
(Partner USTAN)

Partner USTAN has considered noiseless linear amplification, and shown that it is an operation that can only be performed perfectly with vanishing probability of success. Nevertheless, it can be approximated arbitrarily well, and partner USTAN has introduced a weak measurement framework for constructing protocols to achieve this (see Fig. 1). This framework potentially describes a range of possible physical realizations, all that is required is a suitable interaction Hamiltonian, and the ability to prepare and measure states. The resulting protocols achieve approximate noiseless amplification with some probability of success, and success is heralded.

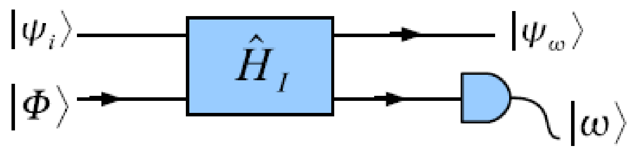


Fig. 1: *Weak measurement model of noiseless amplification. The weak value of the pre and post-selected system is imprinted on the probe system. For an interaction Hamiltonian of the formHI=hκOn and certain post-selections, the transformation on the probe approximates noiseless amplification. Here n is a photon number operator and O is the operator which can describe different measurements dependent on the particular physical implementation of the scheme and which weak value is imprinted on the probe.*

An advantage of this weak measurement approach is that many different physical apparatus may be described by the same formalism. In principle a wide range of combinations of physical ancilla systems, interactions and measurements can give rise to a physical realization of approximate noiseless amplification. This has already been shown to be a powerful approach in demonstrating that existing models of Gaussian continuous variable entanglement concentration can all be thought of as special cases of the weak measurement formalism considered here. Partner USTAN considered in detail the application of the scheme to cloning of weak coherent states, and discuss the performance of one possible physical implementation

Model	β	Fidelity	P_S
Weak model, $\kappa_T = 4 \times 10^{-5}$	0.2	> 0.99	20 %
Weak model, $\kappa_T = 2 \times 10^{-5}$	0.2	> 0.9996	4 %
Weak model, $\kappa_T = 2 \times 10^{-5}$	0.5	> 0.995	4 %
Linear optics	0.2	> 0.999	0.5 %
Linear optics	0.5	≈ 0.99	0.5 %

Table. Comparison of the performance of the weak measurement protocol to Ralph and Lund's linear optics protocol.

For the cloning of weak coherent states, some numerical values for the fidelities and corresponding probabilities of success achievable by the weak value model developed by partner USTAN are given (see Table) in comparison with those achieved by the linear optical model of Ralph and Lund {1}. For fidelities comparable to those achieved by the linear optical model of Ralph and Lund, protocol of partner USTAN has a probability of success that is an order of magnitude larger. Further, at the fidelity of 0.99 their protocol gives a probability of success as high as 20%.

The presented scheme of partner USTAN is of interest as an example of how weak values may be exploited to perform useful tasks in quantum information theory. Another example of weak values in quantum information is the entanglement concentration protocol. Based on their previous work, partner USTAN started to develop a photon-subtracting protocol for atomic entanglement distillation using weak measurements method. An indispensible requirement for the protocol is a light-atom beamsplitter interaction. As a first step towards entanglement concentration protocol, partner USTAN has suggested how to implement an effective beamsplitter between light and atomic ensemble which can approximate the proper beamsplitter transformation for the relevant quadratures with arbitrary precision. For this, the light mode is coupled to an atomic ensemble *A* via the QND Hamiltonian, the quadratures of both systems are then rotated and the emerging light field is reflected back into the atomic ensemble for a further QND interaction. In the case of the atoms, the quadratures represent the re-scaled collective spin operators. The multi-pass QND protocols of similar type were studied for their use in light-state retrieval. There, however, the interaction Hamiltonian is in general not identical to a beamsplitter one. Partner USTAN has explored the conditions on the interaction constant and on the input states of light mode, for which the interaction between light and atomic ensemble is best approximated to that of a beamsplitter. If the interaction constant is small, it is possible to use this effective beamsplitter to increase the entanglement between two entangled atomic ensembles. This could be done by performing beamsplitter interactions on both ensembles, combining the emerging light beams on a real beamsplitter and taking a measurement of one of the light modes.

References:

{1} T. C. Ralph and A. P. Lund, e-print: arXiv:0809.0326v1 (2008).

Publications:

D. Menzies and S. Croke, *Noiseless linear amplification via weak measurements*, quant-ph arXive:0903.4181.

Reported progress towards Deliverable 3.5: (Unexpected extra progress)

Novel Sources for Polarisation Squeezing and Polarisation Entanglement using Photonic Crystal Fibres

(Partners FAU and DTU)

Efficient sources of squeezed light are essential for the creation of CV entanglement used in entanglement distillation protocols. Photonic crystal fibres (PCF) can be tailored to introduce a high effective nonlinear Kerr effect and to create lower amounts of excess noise compared to standard fibres. Taking advantage of these features and using ultrashort pulses we create polarisation squeezed states with notably higher purity than obtained in standard fibres. The squeezed states are produced by pulses of equal polarisation counter propagating along the same fibre axis undergoing nearly identical spectral and temporal changes (Fig. 1 - left). Overlapping these pulses in modes of mutually orthogonal polarisation enables the production of polarisation squeezing.

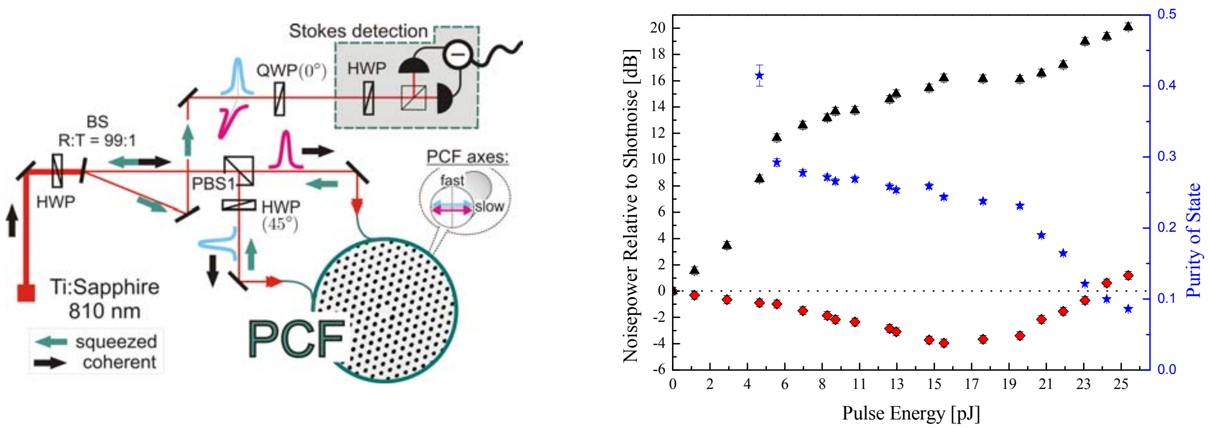


Fig. 1: ***Left panel:*** *Schematic of the experimental squeezing setup. BS: beam splitter PBS: polarising beam splitter. HWP: half-wave plate. QWP: quarter-wave plate.* ***Right panel:*** *Measured noise power versus the optical pulse energy. Red squares and black triangles show squeezing and anti-squeezing, respectively (left scale). We observed a maximum squeezing of −3.9±0.3 dB with an anti-squeezing of 16.9±0.3 dB. The blue stars show the purity of the squeezed state (right scale). All data are measured at a frequency of 17 MHz. The squeezing is only corrected for electronic detector noise which is 13 dB below the shot noise.*

We generated a maximum squeezing of −3.9 ± 0.3 dB and a corresponding anti-squeezing of 16.8 ± 0.3 dB (Fig. 1-right). Since the excess noise is about 8 dB lower than in standard fibres the purity of our squeezed states is more than three times higher. By exploiting both polarisation axes of the polarisation maintaining PCF we can generate two independent polarisation squeezed beams that can be used to create polarisation entanglement. We present results of the PCF squeezer and discuss the progress in creating entanglement with this novel setup

Furthermore we have investigated the generation of polarisation squeezing in photonic crystal fibres by using a single pass setup where both the slow and fast axis have to be utilized. While this experimental setup leads to very good results using standard fibres it shows some drawbacks using PCFs. This is mainly due to the different dispersion properties for the orthogonal fibre axes which introduced different spectral evolutions for the orthogonal pulses. In order to minimize these problems we are investigating other kinds of PCFs which have promising dispersion properties and hold the promise to minimize the photon-phonon coupling.

Publications:
J. Milanovic, M. Lassen, U. L. Andersen, and G. Leuchs, *Novel Method for Polarization squeezing with Photonic Crystal Fibers*, arXiv:0902.4597v1 [quant-ph].

Conference presentations:
J. Milanovic, M. Lassen, G. Leuchs, and Ulrik. L. Andersen, *Improved Methods for Polarization Squeezing with Photonic Crystal Fibers (PCFs),* 3rd International Conference on Quantum Information (ICQI), 2008, Boston MA, USA.

J. Milanovic, M. Lassen, C. Marquardt, U. L. Andersen, and G. Leuchs, *Novel Method for Polarization Squeezing and Polarization Entanglement with Photonic Crystal Fibers*, DPG Spring Meeting, 2009, Hamburg, Germany.

Reported progress towards Deliverable 3.5: (Unexpected extra progress)
Capacity of memory bosonic Gaussian channels
(Partner ULB)

Most quantum communication protocols to date have been based on discrete variables, i.e., are described in a finite-dimensional Hilbert space. In the case of optical communication, however, the quadrature components of the light field make *continuous variables* that are especially powerful because of their associated detection scheme, namely homodyne detection. This is well illustrated with CV quantum key distribution, which now appears as a credible alternative to single-photon based quantum key distribution. This gives a strong incentive on to a better understanding of the communication capacity of continuous-variable quantum channels, in particular bosonic Gaussian channels.

In this preliminary work (more details will be provided at the end of the second year of COMPAS), Partners ULB has addressed the classical capacity of a quantum bosonic channel *with memory*, which is modeled by correlated noise emerging from a Gauss-Markov process. This leads to evaluating the supremum of the information transmission rate via a multimode Gaussian bosonic channel subject to a common energy constraint at the limit of an infinite number of modes. It was shown that, if the standard conjecture that Gaussian input states minimize the output entropy of Gaussian channels is taken for granted, the optimal modulation results from a ``*quantum waterfilling*'' solution that is analogous to the optimal modulation for parallel classical Gaussian channels. The optimal multimode input entangled state was derived analytically, which makes it possible to compute the capacity of this memory channel. The extension to the case of broadband bosonic channels with colored Gaussian noise is the subject of further investigation within COMPAS.

Publications:

J. Schäfer, *Classical capacity of a bosonic memory channel with Gauss-Markov noise*, Ms Thesis (Université libre de Bruxelles and Johannes-Gutenberg Universität Mainz, 2009).

J. Schäfer, E. Karpov, D. Daems, and N.J. Cerf, *Capacity of a bosonic memory channel with Gauss-Markov noise*, in preparation.

4. Deliverables and milestones tables

Deliverables (excluding the periodic and final reports)

TABLE 1. DELIVERABLES									
Del. no.	Deliverable name	WP no.	Lead beneficiary	Nature	Dissemination level	Delivery date from Annex I (proj month)	Delivered Yes/No	Actual / Forecast delivery date	Comments
D1.1	Characterization of CV entanglement	1	7	R	PU	12	Yes		
D3.4	Filtering of noise in CV systems	3	9	R	PU	24	Yes		Delivered in advance (extra work in progress)
D3.5	Distillation or concentration of CV entanglement	3	9	R	PU	36	Yes		Delivered in advance (extra work in progress)

Milestones

TABLE 2. MILESTONES							
Milestone no.	Milestone name	Work package no	Lead beneficiary	Delivery date from Annex I	Achieved Yes/No	Actual / Forecast achievement date	Comments
MS1	Experimental quantum error/erasure correction	3	9	12	Yes		

5. Project management

Workpackage 4 is devoted to the project management and knowledge dissemination. The coordinator (ULB) and deputy coordinator (UP) are responsible for it.

Project website

The project website (Task 4.1, Deliverable 4.1) has been established on time, at month 6 of the project. It is available at:

http://optics.upol.cz/compas/

These pages contain up-to-date information about the project goals, the scientific activities of the partners and the project results. Major achievements are highlighted, and a list of all publications with full access to reprints/preprints is included. A link to web sites of all partners is also provided.

This website will be constantly updated and improved during the course of the project. This is the first action towards knowledge dissemination.

Conference and meeting organization

Among the project objectives towards knowledge dissemination, it was planned to organize workshops especially devoted to continuous-variable quantum information processing, following on the series of "CV-QIP workshops" which has been initiated in 2002 by members of the present project (ULB, CNRS-IO, NBI) and has been running successfully since then. The list of previous workshops is the following:

CV-QIP'02 (Brussels, April 2002, ULB, CNRS-IO, NBI)
CV-QIP'03 (Aix-en-Provence, April 2003, CNRS-IO, ULB)
CV-QIP'04 (Veilbronn, April 2004, FAU, ULB).
CV-QIP'05 [ESF Exploratory Workshop] (Prague, April 2005, UP, ULB)
CV-QIP'06 (Copenhagen, May 2006, NBI, ULB)
CV-QIP'07 (St. Andrews, April 2007, USTAN, ULB)

In 2008, the coordinator (N.J. Cerf, ULB) chaired a major event under the auspices of the International Solvay Institutes (Brussels), which was entitled:

1st Solvay workshop on Bits, Quanta, and Complex Systems: Modern approaches to photonic information processing.

It took place in the Palace of the Academies in Brussels from April 30 to May 3, 2008, and was devoted to the recent scientific advances at the interface between photonics, physics (including both nonlinear and quantum physics), and information sciences. The workshop consisted of 7 half-day sessions, with one discussion leader and 3 invited speakers per session. It was a great opportunity to listen to some of the world renowned experts in these interconnected disciplines, as well as to discover new trends that result from the convergence of these fields.

Continuous-variable quantum information theory was one of the themes discussed during this workshop, and a good fraction of the COMPAS members attended it. Given this fact, as well as the important workload that this organization implied, it was decided that no separate CV-QIP workshop would be organized in 2008 within COMPAS.

In 2009, given that the first year of COMPAS ends on March 31st, it was too short to organize a CV-QIP workshop that would coincide with the first project review meeting, as initially planned. Since, on the other hand, partner UP organizes two major conferences in 2009 (see below) it was therefore decided that a section of these conferences devoted to continuous variables would be placed under the banner of COMPAS (which contributes to a small fraction of the budget), and would then be a substitute to the CV-QIP'09 workshop. The conferences are:

11th International Conference on Squeezed States and Uncertainty Relations (ICSSUR'09)
Olomouc, Czech Republic, June 22 – 26, 2009

4th Feynman Festival
Olomouc, Czech Republic, June 22 – 26, 2009

Again, many partners of the COMPAS project will attend and give talks during these conferences, in particular in Section B of ICSSUR'09 which is devoted to continuous variables, quantum-information processing with continuous variables, and the generation of CV states. For this reason, the first Project Coordination Meeting of COMPAS will be held on an informal basis during this conference.

Planned activities in year 2 and 3

The first workshop that will be fully organized within COMPAS is planned for June 2010. It will be organized by partner MPG, and will also be the occasion for having the second Project Coordination Meeting. It will hopefully be possible to make it coincide with the second year review meeting of the project. It is:

7th Continuous-Variable Quantum Information Processing (CV-QIP'10) workshop.
To be held in Ammersee (near Munich), Germany, June 11-14, 2010.

The following workshop organized within COMPAS, namely CV-QIP'11, is tentatively planned for the Spring 2011. It should take place in Berlin, organized by partner POTSDAM.

These past meetings and planned activities make the content of the work reported under Task 4.2 (Project meetings and workshops). In addition, our work under Task 4.3 (Contribution to activities at the level of FET-Open) was reported in Section 2 of this report, so we do not repeat it here. It concerns in particular the publication of project results in widely accessible and, where available, openly accessible science and technology journals, the participation in FET-organized events, for example conferences, dedicated workshops and working groups, consultation meetings, summer schools, online forums, etc.

Finally, let us mention that there have been numerous bilateral collaboration visits among the project partners during the first year of the project, as reflected by the large number of joint works.

Reflection on the outlook of research in continuous-variable QIPC

This is the content of Task 4.4. The coordinator (ULB) and deputy coordinator (UP), helped by all workpackage leaders, are working on a short report on the outlook of the research in continuous variables QIPC (contribution to the area of quantum information, impact on other areas of research, in particular quantum optics). This short report will be based on the brainstorming sessions on the potential “medium-term scientific spin-offs” of continuous variables that will be organized during the CV-QIP workshops. Since, as explained earlier, there was no such workshop in 2008 and 2009, we expect to be able to deliver this short report as an outcome of the CV-QIP’10 workshop.

6. Explanation of the use of the resources

TABLE 3.1 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY ULB FOR THE PERIOD 1			
Work Package	Item description	Amount	Explanations
1,3,4	Personnel costs	34.903,85€	Salaries of 1 postdoc, David Daems, for 1 month full-time and 6 months half-time, 1 postdoc, Julien Niset, for 1 month full-time, and 1 administrative person, Valérie Baijot, for 7 months half-time
1,3,4	Major cost item	2.329,85€	Various travel expenses
	TOTAL DIRECT COSTS	37.277,91€	

TABLE 3.2 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY MPG FOR THE PERIOD 1			
Work Package	Item description	Amount	Explanations
2	Personnel costs	17.340,49€	12 months PhD student
	TOTAL DIRECT COSTS	17.340,49€	

TABLE 3.3 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY ICFO FOR THE PERIOD 1			
Work Package	Item description	Amount	Explanations
2	Personnel costs	24.734,61€	8 months salary of Post-Doc
2	Major cost item 'Travel and subsistence'	993,24€	Attendance of the following meetings: - Congress MATHQCI 2008 (Madrid) - Registration in the NFQC08 Congress (Dresden) - Visit to the group "Quantum Optics an Statistics" (Freiburg) - Conference about "Quantum Coherence and Decoherence" (Benasque)
2	Remaining direct costs	168,60€	Office consumables
	TOTAL DIRECT COSTS	25.896,45€	

TABLE 3.4 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY UP FOR THE PERIOD 1			
Work Package	Item description	Amount	Explanations
1,2,3	Personnel costs	17668,00 €	Salary of 1 post-doctoral researcher (6.5 person-months) and a part of a salary of 1 senior researcher (3.5 person-months)
	TOTAL DIRECT COSTS	17668,00 €	

TABLE 3.5 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY USTAN FOR THE PERIOD 1			
Work Package	Item description	Amount	Explanations
3	Personnel costs	7028,03€	Salary of 1 PhD student for 6 months(maintenance scholarship)
3	Remaining direct costs	4069,57€	Travel expenses
	TOTAL DIRECT COSTS	11097,60€	

TABLE 3.6 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY POTSDAM FOR THE PERIOD 1			
Work Package	Item description	Amount	Explanations
1, 3	Personnel costs	18699,00 €	14968 € for additional staff (2 PhD students – half time; 3730 € for permanent staff (Prof. Eisert)
1, 3	Major cost item 'Travel'	188,00 €	
	TOTAL DIRECT COSTS	18887,00 €	

TABLE 3.7 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY CNRS/IO & CNRS/ENS FOR THE PERIOD			
Work Package	Item description	Amount	Explanations
1,2	Personnel costs	133 258,60€	Salary of permanent staff involved in the project, and working at CNRS (Elisabeth Giacobino, Philippe Grangier, Florence Fuchs, 10 pm total), UPS (Gaétan Messin, Rosa Tualle-Brouri, 7 pm total), and UMPC (Alberto Bramati, Julien Laurat, 5 pm total). The total of 22 pm is as planned on the contract , with 10 pm in WP1 and 12 pm in WP2.
	TOTAL DIRECT COSTS	133 258,60€	

TABLE 3.8 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY NBI FOR THE PERIOD 1			
Work Package	Item description	Amount	Explanations
2	Personnel costs	21.610,00€	4 PM for Post Doc. Anne Marie M. Louchet
2	Consumables, Social costs	232,00€	Obliged social costs for Anne Marie Louchet
	TOTAL DIRECT COSTS	21.842,00€	

TABLE 3.9 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY DTU FOR THE PERIOD 1			
Work Package	Item description	Amount	Explanations
3	Consumables	5.131,00€	Electronics, Optics
	TOTAL DIRECT COSTS	5.131,00€	

TABLE 3.10 PERSONNEL, SUBCONTRACTING AND OTHER MAJOR DIRECT COST ITEMS FOR BENEFICIARY FAU FOR THE PERIOD 1			
Work Package	Item description	Amount	Explanations
3	Personnel costs	1.995,06 €	Salary of 1 Ph.D. student for 1 month
	TOTAL DIRECT COSTS	1.995,06 €	