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 2009 to 31st March 2010

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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: ....31..../ .May....../ .2010.........

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

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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 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 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/

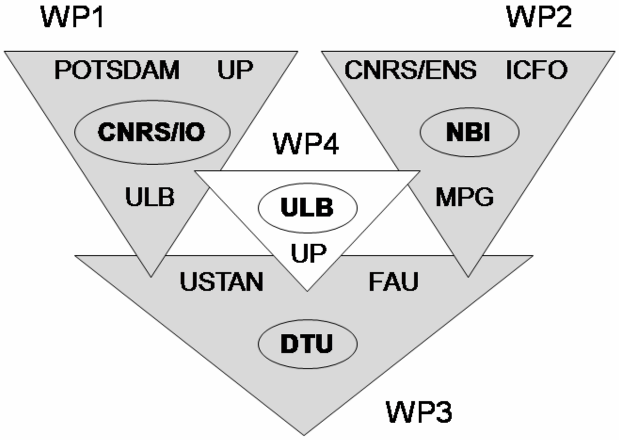
It is anticipated that the COMPAS project will have a strong impact on the future of ICT-related technologies and further strengthen the pan-European cooperation in a research area where Europe has started to establish itself at the leading edge.

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 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 being 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 2nd 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 01/04/09 to 31/03/10
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 2 of the project

A significant progress has been achieved in the area of measurement-induced nonlinear operations. Partner UP proposed an experimentally feasible scheme for implementing arbitrary transformations on traveling light beams that are represented by operators diagonal in Fock state basis. The scheme is based on multiple photon addition and subtraction operations, which are coherently combined in order to effect the desired operation. This technique can be used to emulate Kerr nonlinearity that is essential for designing CV quantum gates. Another intriguing application that has been investigated is the probabilistic noiseless amplification of light, which increases the amplitude of coherent states without adding noise. This may be useful, e.g., for (partial) compensation of losses in quantum communication or for CV entanglement concentration. The noiseless amplifier can be even further simplified by replacing the single-photon addition by addition of thermal noise, which is much easier to implement experimentally. The resulting amplifier adds a little noise, but it can still strongly improve the phase resolution in experiments with coherent states.

Partner ICFO investigated methods for the generation of CV graph states suitable for universal CV one-way quantum computing. Two-body Hamiltonians were identified which have such states as ground states. Partner POTSDAM showed that measurement-based quantum computing with Gaussian resource states is not possible without employing the fully fletched machinery of fault tolerance. To address this bottleneck, partner POTSDAM extended the formalism of matrix-product states to the situation of continuous-variable quantum information, where the logical information is encoded in finite-dimensional abstract spaces - and hence error correction is feasible - while the physical system is continuous. Partners POTSDAM and NBI also proposed and successfully tested a method of deriving certifiable quantitative lower bounds to negativity of Wigner function of a state from measurement data. Partner ULB also further analyzed the link between the non-Gaussianity of a state and the negativity of its Wigner function (Hudson's theorem), along with new uncertainty relations that depend on the non-Gaussianity of the state. Partner ICFO devised new method for derivation of Bell inequalities based on multi-linear contractions. This approach is better tailored for CV systems and could potentially pave the way towards loophole-free Bell test. Partner POTSDAM extended the detector tomography scheme to cover also weak instances of homodyning. Interestingly, these techniques can be used to quantify entanglement in continuous-variable distillation schemes.

On the experimental side, partner CNRS/IO focused on optimization of experimental tools and techniques for the generation of Fock states and cat-like states of light beams. Since efficient photon counting is a crucial prerequisite for achieving these goals, the CNRS/IO group worked on cryogenic photon counters VLPC capable of resolving the number of photons in a pulse. Resolution of up to 4 photons was achieved and a quantum efficiency of 20% at 850 nm was clearly identified. Moreover, partners CNRS/IO and NBI developed a complete multimode theory for projective photon counting that enables optimization of experimental scheme for cat state generation. In particular, it was found that state purity can be greatly improved by increasing the size of the pump beam. Another essential ingredient for production of Fock and cat-like state is a source of squeezed and entangled states of light. Partner FAU succeeded in generation of broadband polarization squeezed vacuum. By combining wavelength and polarization degrees of freedom, “macroscopic Bell states” were produced, which are high-gain analogues of two-photon Bell states. Partners FAU and DTU also investigated a novel promising configuration for generation of nonclassical light based on a nonlinear interactions in a whispering gallery mode (WGM) resonator. This toroidal resonator exhibits very small volume and high quality factors, which strongly enhances optical nonlinear effects. Second harmonic generation was observed with saturation pump power of 3 mW that is two orders of magnitude lower than previous state of the art. In subsequent preliminary experiments, squeezing produced by highly non-degenerate parametric down-conversion in WGM resonator was observed.

Finally, as an important step towards the development of basic operations for CV quantum computing, partner CNRS/IO experimentally implemented a probabilistic noiseless amplifier for weak coherent states. The demonstrated noise-free amplification is based on quantum scissors scheme and was fully characterized by homodyne tomography. The amplifier exhibits negative equivalent input noise and a nominal amplitude gain g=2 that decreases with increasing amplitude of the input coherent state. Refined version of the noiseless amplifier could be used for amplification of cat states formed by superposition of two coherent states, which could greatly facilitate future realization of cat-states quantum computing schemes.

Task 1.1: Basic concepts and theoretical tools for CV information processing

Deliverable 1.1: *Characterization of CV entanglement*

Status: Due month 12; Delivered on time; Additional progress reported

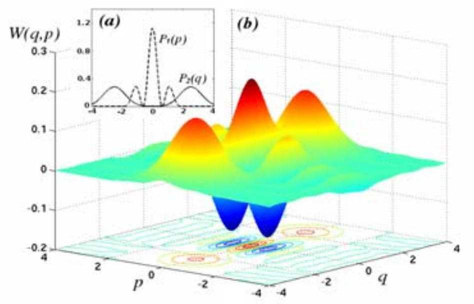
Partners: ULB, POTSDAM, ICFO, CNRS/IO, DTU, FAU

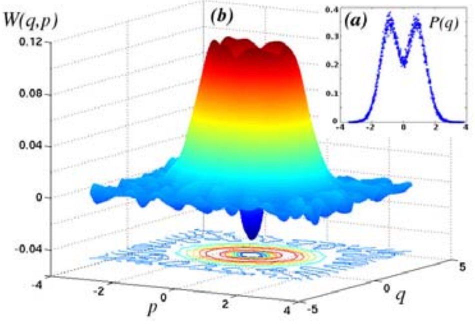
This task first aims at characterizing and detecting quantum entanglement in multipartite non-Gaussian states. In contrast to the case of Gaussian states, few results exist for non-Gaussian states. In view of the importance of the latter states in this project, one of the goals of the present project 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 additional results have been obtained that are related to CV entanglement and non-locality, and are therefore reported here.

Additional progress towards Deliverable 1.1:
Directly estimating non-classicality of CV states
(Partner POTSDAM)

Work has been performed on the quantification of the resources needed for CV entanglement distillation and several first results have been obtained in this direction. In particular, the capability to function as such a resource is intimately connected to the negativity of the Wigner function of the respective state. How to certify the negativity of the Wigner function, which is also a measure for the non-classicality of a quantum state, has been studied by us in great detail. We have derived certifiable quantitative lower bounds from measurement data. The important point is that only two quadrature measurements and no full quantum-state tomography are needed and that we obtain a worst case estimate also when the data are affected with errors. These results can be used as a starting point to certify the entangling distillation power of quantum states in a quantitative fashion.

Figures:





Publication:

A. Mari, K. Kieling, B. Melholt Nielsen, E. S. Polzik, and J. Eisert, Directly estimating non-classicality, arXiv:1005.1665.

Additional progress towards Deliverable 1.1:

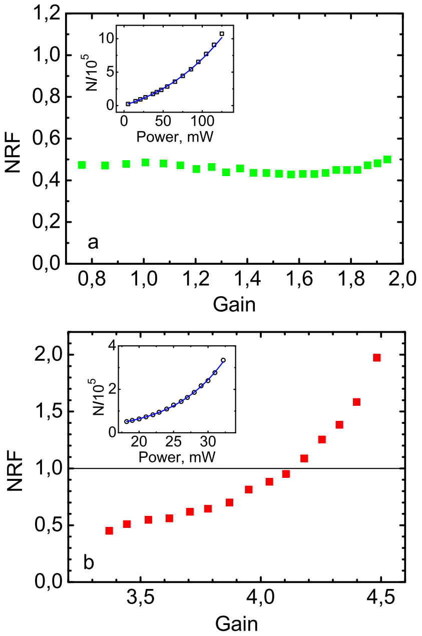
Experimental generation and direct detection of broadband mesoscopic polarization-squeezed vacuum

(Partner FAU)

Squeezed vacuum, the state generated at the output of an unseeded optical parametric amplifier (OPA), is an example of a macroscopic system with quantum behavior. Despite its name, squeezed vacuum can have a huge number of photons. Because all these photons come in pairs, the state contains only even photon numbers.

Using a traveling-wave OPA pumped by strong picosecond UV pulses, we have generated squeezed vacuum states within a broad frequency-angular range. By changing the pump pulse energy we can vary the parametric gain from much less than unity up to 4.5. The corresponding numbers of photons per one longitudinal and transverse mode are up to 10^3. Moreover, by collecting a large number of modes, we are able to get the numbers of photons per pulse on the order of 10^6. This provides a possibility for the direct detection of squeezed vacuum, which we do by means of charge-integrating detectors based on pin diodes. The achieved degree of twin-beam squeezing (4dB) is the best result obtained so far for the case of squeezed vacuum direct detection. Figure 1 shows the noise reduction factor (NRF), defined as the ratio of the difference-signal variance to the sum-signal mean value, as a function of the parametric gain. Nearly constant twin-beam squeezing is observed at the gain values below 2 (Fig.1a). At higher gain values (Fig.1b), NRF grows due to the excess noise in the unmatched transverse modes of twin-beam radiation.

Figure 1:



Two experimental configurations have been realized so far. In the first one, the OPA is frequency non-degenerate, and the twin beams have different wavelengths. In the second configuration, by using two frequency-degenerate OPAs in orthogonal polarization modes, we obtain squeezing in a given Stokes parameter. In the latest version of the setup, combining wavelength and polarization degrees of freedom (a four-mode OPA), we produce 'macroscopic Bell States' (MBS), which are high-gain analogues of the two-photon Bell states.

Publications:

- T. Iskhakov, M. V. Chekhova, and G. Leuchs, "Generation and Direct Detection of Broadband Mesoscopic Polarization-Squeezed Vacuum." PRL 102, 183602 (2009).
- N. Agafonov, M. V. Chekhova, and G. Leuchs, "Two-Color Bright Squeezed Vacuum". arXiv:0910.4831v3 [quant-ph], submitted to PRA (2010).
- Agafonov, M. Chekhova, T. Iskhakov and G. Leuchs, "Multimode Detection of Broadband Squeezed Vacuum." Proceedings of NATO Advanced Research Workshop 'Quantum Cryptography and Computing: Theory and Implementation' Gdansk, Poland, 9-12 September 2009.

Conference Presentations:

- M. V. Chekhova, T. Sh. Iskhakov, G. Leuchs, "Generation and Direct Detection of Broadband Mesoscopic Polarization-Squeezed Vacuum", 18th International Laser Physics Workshop (LPHYS'09), July 13 – 17, 2009, Barcelona, Spain (invited).
- Ivan Agafonov, M. V. Chekhova, T. Sh. Iskhakov, G. Leuchs, "Generation and direct detection of broadband squeezed vacuum", NATO Advanced Research Workshop 'Quantum Cryptography and Computing: Theory and Implementation' Gdansk, Poland, 9-12 September 2009 (invited).

Additional progress towards Deliverable 1.1:

Nonclassical light in a Whispering Gallery Resonator
(Partner FAU, DTU)

For applications in quantum information processing it is of importance to possess efficient and reliable sources of nonclassical light. The second order nonlinearity in a crystalline material is known as a good source of squeezing and entanglement. The quality of whispering gallery mode resonators (WGM) exhibit high quality factors along with small mode volume [1,2,3]. This enormously enhances nonlinear effects. The second order nonlinearity shows a plethora of effects, as squeezing, entanglement [5], competing nonlinearities and dynamics like self pulsing and instabilities [4]. Two and multi-colour-entanglement can be implemented as well. We investigated second harmonic generation(SHG) in the WGM configuration to study the possibilities of these systems for the generation of non-classical light.

Our resonator is made of a 5% MgO-doped z-cut LiNbO3 crystal (see Fig. 1), carefully polished to a toroidal shape. We pump it with a continuous wave Nd:YAG laser at 1064nm. The resonators WGMs for the pump mode have a linewidth of around 10MHz. We applied phase matching and observed SHG with efficiencies up to 10% at as low as 30µW. The saturation pump power was estimated to be at approx. 3mW. This is two orders of magnitude lower than the state of the art in whispering gallery modes. In this low pump power regime, shot noise limited or even sub shot noise pump fields are easily accessible. As a next step we plan to investigate the squeezing and entanglement of both modes involved in the SH process.

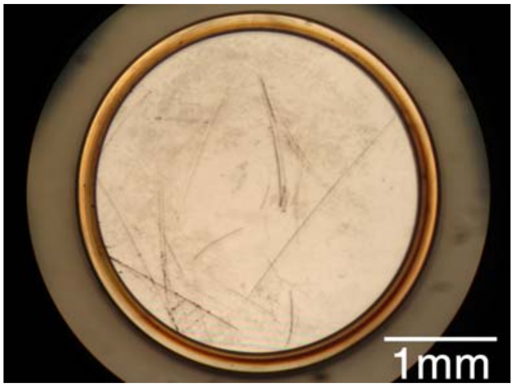


Figure 1: *Polished spheroidal resonator under a light microscope*.

We also observed a self-limiting effect, starting at a certain threshold. Scanning the optical frequency of the pump over one resonance phase matched for SHG, the pump intensity suddenly increases again near the center of the resonance. In parallel, the SH power decreases. A possible explanation could be a competing nonlinear process, namely PDC, starting at a certain threshold. We plan to further investigate this, especially as multiple modes are coupled nonlinearly. Unpublished measurements also showed highly nondegenerate PDC in our WGM resonator. In this preliminary work, we also observed squeezing in twin beam correlations and, for the first time single parametric beam amplitude squeezing far above threshold (to be published).

References:

[1] C. Raman et al., Nature 108, 42 (1921)
[2] A. Matsko et al., IEEE Selected topics on quantum electronics,12 (2006)

[3] V. Ilchenko et al., IEEE Selected topics on quantum electronics, 12 (2006)
[4] P. Drummond et al., Optica Acta 28, 211 (1981); 27, 321 (1980).
[5] C. Fabre et al., J. Phys. France 50, 1209 (1989).

Publications:

J.U. Fürst, D. Strekalov, D. Elser, M. Lassen, U. L. Andersen, Ch. Marquardt, G. Leuchs, "Naturally Phase Matched Second Harmonic Generation in a Whispering Gallery Mode Resonator", Phys. Rev. Lett. 104, 153901, (2010) (featured in APS physics viewpoint)

Conference Presentations:

J.U. Fürst, D. Strekalov, D. Elser, A. Aiello, U. L. Andersen, Ch. Marquardt, G. Leuchs, "Naturally Phase Matched Second Harmonic Generation in a Whispering Gallery Mode Resonator", CLEO/QELS, May 16-21, 2010, San Jose, USA (2010)

Reported progress towards Deliverable 1.1:
Non-Gaussianity bounded uncertainty relation for mixed states
(Partner ULB)

One main problem in CV quantum information is to better understand the non-Gaussian states and operations that are necessary for CV quantum information processing. Non-Gaussian states are well known by now 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 Hudson's theorem: "Among pure states, the only states which have non-negative Wigner functions are Gaussian states".

In year 1, partner ULB had investigated 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). More precisely, we had analyzed the relation between non-Gaussian CV mixed states and non-positive Wigner functions. As a starting point, we had explored 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).

In year 2, we have pursued this work on non-Gaussian mixed states, which led us to the problem of uncertainty relations. We derived an uncertainty relation for a single-mode CV mixed state characterized by its purity and its degree of non-Gaussianity. This extends the purity-bounded uncertainty relation for mixed states that had been derived by V. V. Dodonov and V. I. Man'ko. We can represent our results as a bound in the space of mixed states and we identify the parts realized by states with strictly positive Wigner function. This takes us closer to an exact extension of Hudson's theorem for mixed states and permits us to compare the set of states with strictly positive Wigner functions with the set of states which minimize the derived uncertainty relation.

Publications:

- Mandilara, E. Karpov, and N. J. Cerf, *Extending Hudson's theorem to mixed quantum states*, Phys. Rev. A 79 (2009) 062302.
- Mandilara, E. Karpov, N. J. Cerf, *Non-Gaussianity bounded uncertainty relation for mixed states*, arXiv:0910.3473 [quant-ph].

Conference presentations:

- 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]
- Mandilara, E. Karpov, and N. J. Cerf, *Extended uncertainty relations for mixed states*, SPIE Photonics Europe, Brussels (Belgium), 12-16 April 2010. [CONTRIBUTED TALK]

Additional progress towards Deliverable 1.1:
Bell inequalities with CV entangled quantum states.
(Partner ICFO)

In this work, partner ICFO has studied the use of multi-linear contractions to derive Bell inequalities valid for an arbitrary number of outcomes. These inequalities are better tailored for CV systems and, then, potentially useful for loophole-free Bell tests.

Publications:

- *Bell inequalities from multilinear contractions,* Alejo Salles, Daniel Cavalcanti, Antonio Acín, David Pérez-García, Michael M. Wolf (submitted)
- *Almost all quantum states have non-classical correlations*, A. Ferraro, L. Aolita, D. Cavalcanti, F. M. Cucchietti, A. Acin, arXiv:0908.3157 (to appear in Phys. Rev. A).

Task 1.2: Exploring models of CV quantum computing

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 will 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.

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

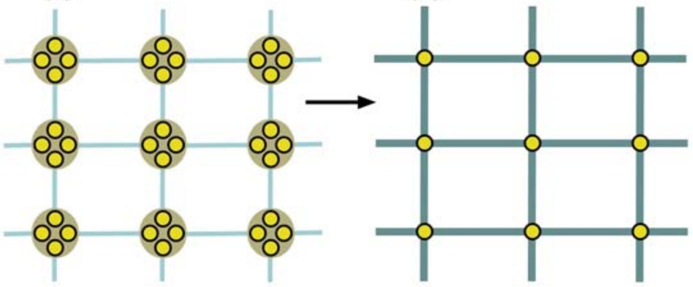
Status: Due month 24; Delivered.

Partners: ULB, UP, POTSDAM

Reported progress towards Deliverable 1.2:
P*otential and limitations of continuous-variable measurement-based quantum computing*
(Partner POTSDAM)

We have extensively investigated the potential and limitations of continuous-variable measurement-based quantum computing (MBQC). This work has focused in particular on identifying obstacles with instances of such an idea based on Gaussian resource states, ones that eventually have to be overcome in any architecture of this type.

Partner POTSDAM investigation revealed in a quantitative fashion the following major obstacle: Under quite general conditions, MBQC with Gaussian resource states is not possible without employing the fully fletched machinery of fault tolerance, even when the resources and all measurements are perfect [1]. Otherwise, any local measurement will only have a finite region of possible impact in the lattice, and computation will hence be finite-ranged and cannot be maintained. The technical argument also introduces novel techniques on Gaussian tensor networks. (Interestingly, the methods introduced here have also led to a new simulation method to simulate quantum fields [3], based on continuous matrix product states, taking a perspective of quantum optical continuous measurement). Physically speaking, the result points towards the necessity of thinking about alternative ideas of continuous-variable quantum computing based on non-Gaussian resource states.



We have also shown that indeed, this path can be taken: In order to circumvent this problem, we have extended the formalism based on matrix-product states, which proved to be very successful in the qubit case, to the situation of continuous-variable quantum optics, where the logical information is encoded in finite-dimensional abstract spaces - and hence error correction is feasible - while the physical system is continuous. The framework introduced allows us both to systematically classify the possible resource states and construct explicit examples.

We have found a scheme based on the interaction between a single atom and light modes where single qubit operations can be performed by feasible homodyning-type measurements. Light has to be prepared in coherent states only, and entangling gates can also be shown to be feasible. This scheme also allows for purely optical implementations. This scheme is physically a continuous-variable scheme for quantum computing, but makes heavy use of non-Gaussian states and can be viewed as a hybrid, as logical information is always strictly encoded in finite-dimensional systems, as it should be for rendering error correction and fault tolerance possible. Seen as a small-scale computing device, it hence also links to other hybrid ideas pursued here, in particular hybrid quantum repeater and distillation schemes.

Publications:

[1] M. Ohliger and J. Eisert, *Efficient continuous-variable measurement-based quantum computing*, in preparation (2010).

[2] M. Ohliger, K. Kieling, and J. Eisert, *Limitations of quantum computing with Gaussian cluster states*, arXiv:1004.0081.

[3] T.J. Osborne, J. Eisert, F. Verstraete, *Holographic quantum states*, arXiv:1005.1268.

Reported progress towards Deliverable 1.2:
Cluster states and graph states with continuous variables
(Partner ICFO)

Partner ICFO has got results on CV graph states and Hamiltonians. Basically, we consider the generalization of graph states (which are fundamental states for QI applications in the discrete cases) and construct Hamiltonians which have these states as ground states. Interestingly, one of these states is the CV cluster state, which is universal for quantum computation. Thus, we have a two-body CV Hamiltonian whose ground state allows measurement based quantum computation.

We also have results on the study of thermodynamical concepts in systems of coupled Harmonic oscillators. The goal is to analyze when sub-blocks of a thermal state correspond to a thermal state at the same temperature as the whole state. The corresponding publication will also appear soon.

Publications:

Macroscopic bound entanglement in thermal graph states, D. Cavalcanti, L. Aolita, A. Ferraro, A. Garcia-Saez, A. Acin, New J. Phys. 12, 025011 (2010)

Reported progress towards Deliverable 1.2:

Engineering quantum operations on traveling light beams

(Partner UP)

Partner UP investigated which more complex quantum operations on the states of traveling light beams can be engineered by combining the elementary techniques of photon subtraction and photon addition. In particular, partner UP proposed and analyzed a scheme for approximate probabilistic realization of an arbitrary operation that can be expressed as a function of photon number operator n. This class of transformations includes for instance the Kerr nonlinearity described by a unitary operation $U=\exp(-i\phi n^2)$, or a noiseless linear amplifier $V = g^n$, where $g > 1$ is the amplification gain.

The scheme is depicted in Fig. 1. In order to implement an operation that is a polynomial of order N in photon number operator, N photons have to be added and also N photons have to be subtracted from the input state. The photon addition is achieved by feeding the state into the input signal port of a nonlinear crystal NLC where pairs of correlated signal and idler photons are generated in the process of parametric down-conversion. The photodetector D_1 counts the number of emitted idler photons N which is equal to the number of photons added into the signal mode.

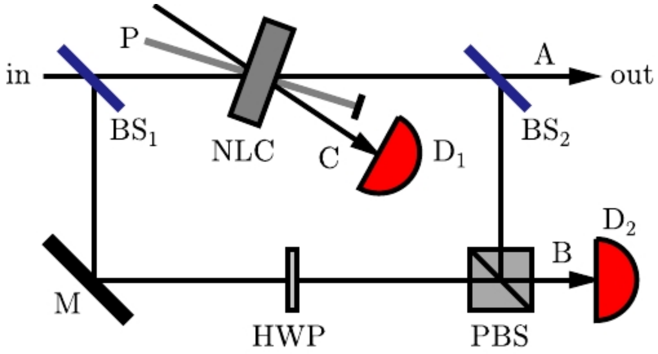


Fig. 1: *Linear optical implementation of operators that are polynomials in photon number operator. The scheme consists of unbalanced beam splitters BS_1 and BS_2, polarizing beam splitter PBS, half-wave plate HWP, mirror M, nonlinear crystal NLC pumped by a strong laser pulse P, and two detection blocks D_1 and D_2. The detection block D_1 counts the number of photons in mode C. Detection block D_2 projects the state in mode B onto a specific entangled N-photon polarization state.*

The photon subtraction is performed by splitting a tiny part of the signal beam off a highly unbalanced beam splitter followed by detection of the number of reflected photons. A crucial feature of the scheme in Fig. 1 is that the photon subtraction may occur either before or after the photon addition. The photons reflected off beam splitters BS_1 and BS_2 are recombined on a polarizing beam splitter PBS such that their polarization states are orthogonal but all other degrees of freedom are made indistinguishable to guarantee maximum visibility of multiphoton interference. The detector D_2 represents a detection block that is capable of making projection onto an arbitrary N-photon polarization state, which can be achieved by linear optics and APDs. The projection made by the detection block D_2 specifies the implemented operation. An arbitrary operation that can be expressed as a polynomial of order N in photon number operator can be realized in this way. Due to such versatility, the proposed scheme can find many applications in quantum information processing such as implementation of quantum gates, probabilistic error-free quantum cloning, or entanglement distillation.

An interesting example of application is the emulation of Kerr nonlinearity that can be used to generate highly non-classical states of light beams and, together with Gaussian operations, is sufficient for universal quantum computing. Quantum mechanically, Kerr effect can be described by a Hamiltonian proportional to the square of photon number operator and the resulting unitary transformation reads $U=\exp(-i\phi n^2)$. For small phase shifts and n we can approximate this transformation by a polynomial $1-i\phi n^2$. This latter operation can be accomplished with the scheme shown in Fig. 1 and requires subtraction and addition of two photons. The performance of this approximate emulation of Kerr nonlinearity is illustrated in Fig. 2, where the phase and amplitude modulation of Fock state amplitudes achieved by the emulation scheme are plotted, $A_n e^{i\Phi n}=1-i\phi n^2$.

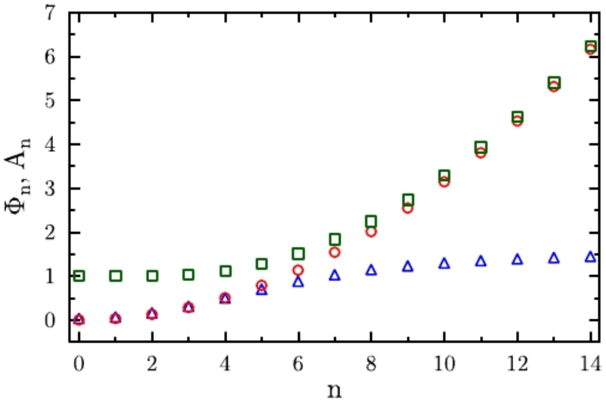


Fig. 2: *Kerr nonlinearity emulation. Plotted are the nonlinear phase shifts* Φ_n *(blue triangles) and Fock state amplitude modulation factors* A_n *(green squares, ideally* $A_n=1$*) induced by the transformation emulating Kerr nonlinearity with nonlinear phase shift π/100. Also shown for comparison is the phase shift corresponding to the true Kerr nonlinearity (red circles). In this particular example, the emulation of Kerr effect works well on the subspace of Fock states |n> with n<=4.*

Publications:

J. Fiurášek, *Engineering quantum operations on traveling light beams by multiple photon addition and subtraction*, Phys. Rev. A **80**, 053822 (2009).

Task 1.3: Engineering non-Gaussian states of light

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.

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

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

Partners: CNRS/IO

Reported progress towards Deliverable 1.3:

Cryogenic photon counters for photon-number resolving measurements
(Partner CNRS/IO)

High-N Fock states are generally obtained using measurement-induced nonlinearities and imply photon number measurements. For that purpose the CNRS/IO group has been working on cryogenic photon counters, with the ability to resolve the number of photons in a pulse. Preliminary results obtained with a VLPC device (Visible Light Photon Counter) were already presented in the Y1 report. Since then Florence Fuchs, engineer in the CNRS/IO group, obtained several improvements: the number of discriminated photon is up to 4, with a quite clear discrimination of 2 and 3 photons. Furthermore, a quantum efficiency of 20% at 850nm is now clearly determined. Such a value is at the borderline of performances obtained using coincidence events on avalanche photodiodes (APD), and decisions should be taken now concerning the advisability to continue with these photon counters, or to look for more efficient ones, or even to use standard APD devices.

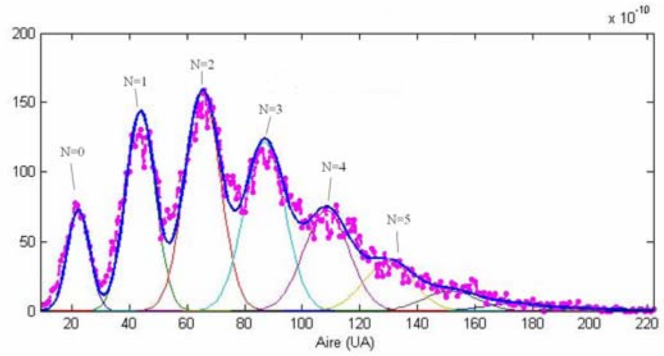


Figure: *The graph (pink dots: experimental values – blue line: Gaussian fit) represents the area signal normalized histogram that exhibits peaks corresponding to each value of the photon number N. Up to 4 photons can be clearly distinguished.*

Reported progress towards Deliverable 1.4:
Generation of monomode and multimode cat states
(Partner CNRS/IO)

In the first year, partner CNRS/IO had reported an experimental demonstration of non-local superpositions of quasi-classical (coherent) light states, giving rise to the remote entanglement of two independent cat states. Some special attention to the purity of the generated states is required within the context of this task, however, in order to envision concrete applications in quantum computing.

The CNRS/IO group developed for that purpose, in collaboration with the team of Professor Anders Sørensen, from the Niels Bohr Institute of Copenhaguen, a complete multimode theory for projective photon counting measurements. This study involves a new general method called mode reduction that reduces the multimode model to an effective two-mode problem. It allows an explicit description of spectral and spatial distortions of light pulses, and it leads to a quantitative understanding of previous experiments. One main lesson from this work is the critical influence of the size of the pump beam in these experiments based on parametric fluorescence: an important improvement of mode purity should be awaited from an increase of this size, but this implies the use of amplified femtosecond pulses. The CNRS/IO group recently purchased a very stable femtosecond oscillator with a pulse picker in order to achieve this goal.

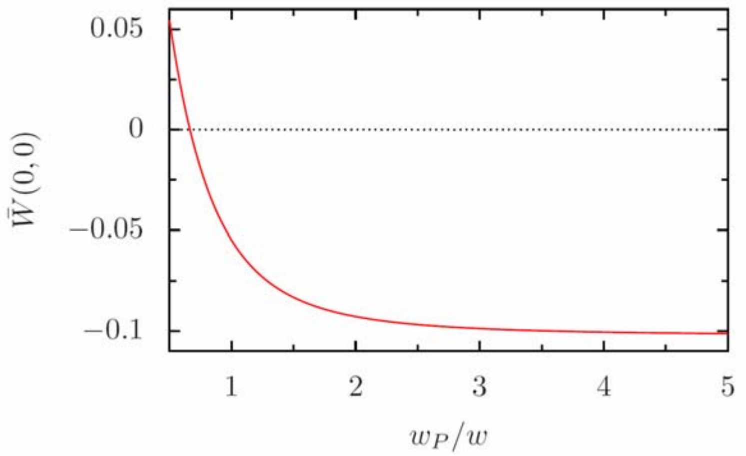


Figure: *Theoretical evolution of the Minimal value of the Wigner function for a small-amplitude cat-like state, as a function of the pump beam waist* w_P. *This negative value is related to the purity of the state.*

Publications:

R. Tualle-Brouri, A. Ourjoumtsev, A. Dantan, P. Grangier, M. Wubs, and A.S. Sørensen, *Multimode model for projective photon-counting measurements*, Phys. Rev. A 80, 013806 (2009).

Task 1.4: Investigating measurement-induced CV information processes

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.

Deliverable1.5: ***Measurement-induced nonlinear operations***
Status: Due month 36; Delivered in advance.

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

Partners: CNRS/IO, ULB, UP, POTSDAM

Reported progress towards Deliverable 1.5:

Nondeterministic optical noiseless amplifier
(Partner CNRS/IO)

A particularly relevant measurement-induced CV quantum operation that has attracted much attention over the last year is the noiseless amplification of light. Such an operation is a priori forbidden by quantum mechanics, which impose that any phase-independent amplifier has to introduce some excess noise. This is rooted into unitarity and linearity of quantum evolution, which also prevent perfect cloning of quantum states. A possible way to circumvent this limitation is to interrupt such evolution via a measurement, providing a random outcome able to herald a successful - and noiseless - amplification event. This idea of non-deterministic noiseless amplification was put forward in: T.C. Ralph, and A. P. Lund, “Nondeterministic Noiseless Linear Amplification of Quantum Systems”, in Quantum Communication Measurement and Computing Proceedings of 9th International Conference, Ed. A.I Lvovsky (AIP, New York 2009), pp. 155-160.

The non-deterministic noiseless amplification of a small coherent state has been experimentally demonstrated (and fully characterized with homodyne tomography) by partner CNRS/IO during the second year of the project, following the proposal of T.C. Ralph and A.P. Lund.

The operating principle is depicted on the figure below: a single photon is split on an asymmetric beamsplitter (A-BS) with reflectivity r; a small amplitude coherent state $|\alpha>$ is superimposed with the reflected output of the A-BS on a symmetric beamsplitter (S-BS). A successful run of the amplifier is flagged by a single photon event on detector D_1 and no photons on detector D_2. Conditioned on this event, the transmitted output of the A-BS is the amplified coherent state $|g\alpha>$, where the value of g depends on the chosen reflectivity r of the A-BS.

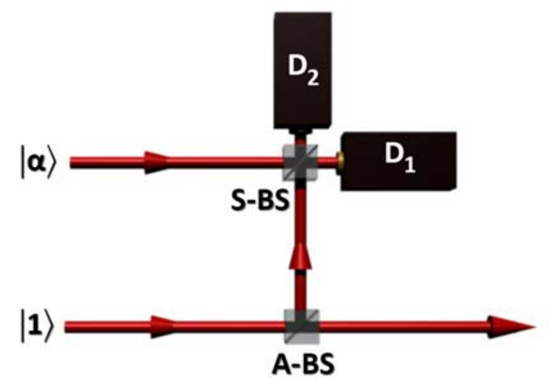
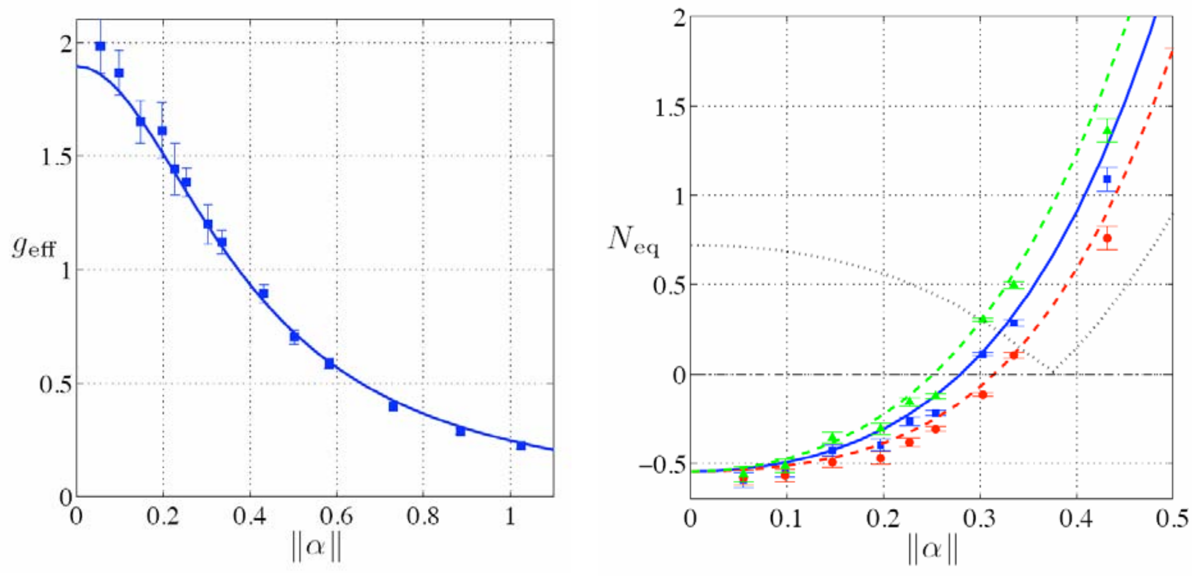


Figure: *Conceptual layout of the noiseless amplifier.*

The effective amplification was quantified by introducing an effective gain $g_{eff} = <X_{out}>/<X_{in}>$, where X_{out} (X_{in}) is the amplitude quadrature of the output (input) field. Experimental data compared well with a model taking into account the main imperfections of the setup: limited quality of our single photon state, due to multipair emission and parasitic processes, imperfect mode-matching between the single photon and the coherent beams, or finite photon counting detection efficiency. The noiseless behavior of our amplifier is analyzed in terms of its “equivalent input noise" N_{eq}, which tells how much noise must be added to the input noise level, in order to mimic the observed output noise for a given gain: Negative values for this quantity were clearly observed, shows that our device not only amplifies the signal but also increases the signal-to-noise ratio. Obviously it remains compatible with Quantum Laws because this phenomenon is observed only for specific heralded events whose outcome rate is as low as the gain is high.



Left figure: *Experimental results for the effective phase-independent gain (markers) compared with model (lines) as a function of the input state amplitude.*
Right figure: *Experimental results for the Equivalent Input Noise: Average value (squares), maximal value (triangles), and minimal value (circles), compared with model (lines).*

Publications:

F. Ferreyrol, M. Barbieri, R. Blandino, S. Fossier, R. Tualle-Brouri, and P. Grangier, *Implementation of a nondeterministic optical noiseless amplifier*, Phys. Rev. Lett. 104, 123603 (2010).

Reported progress towards Deliverable 1.5:

Coherent-state phase concentration by quantum probabilistic amplification
(Partner UP)

Partner UP studied methods for amplification a coherent state capable of preserving, or even improving, its unknown phase - a task which is impossible when only deterministic operations are used. Two probabilistic experimental schemes were proposed [1], linked to the noiseless amplification of light protocol explained above. The first scheme shown in Fig. 1(a), which relies on sequential addition and subtraction of photons, preserves even the purity of the state, but it is more difficult experimentally, mainly because of the involved photon addition operation.

The second amplification scheme shown in Fig. 1(b) is considerably simpler to implement than the first one due to a slightly counterintuitive modification - the photon addition operation is replaced with adding a phase insensitive thermal noise. Intuitively, the effect of noise can be seen as a random modulation. The subsequent photon subtraction then `picks' the coherent states with the highest intensity and, consequently, the correct phase, thus performing the probabilistic amplification of coherent states with unknown phase values. Some noise is added during the process, but the influence of the amplification is stronger and, as a result, the phase resolution is improved.

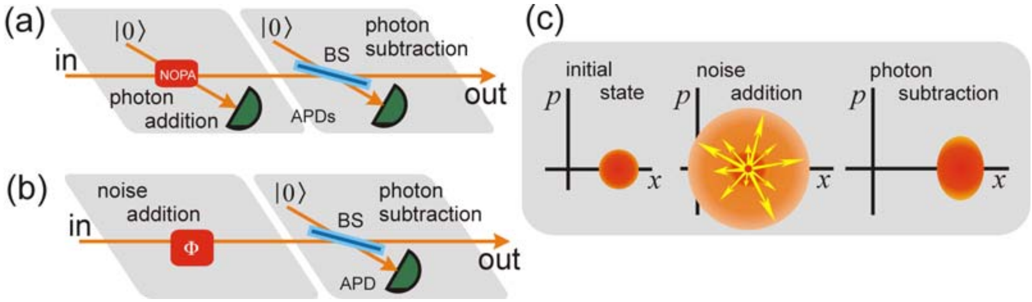


Fig. 1: *(a) Setup for probabilistic amplification by photon addition and subtraction. (b) Setup for probabilistic amplification by noise addition and subtraction. (c) Schematic evolution of the coherent state during the amplification by noise addition.*

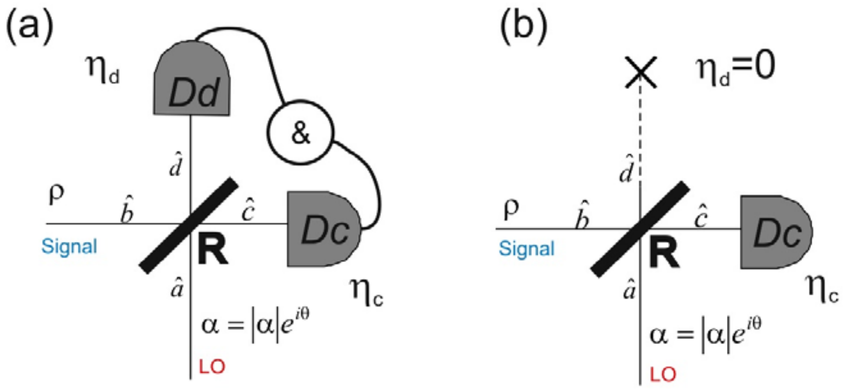
Publications:

[1] P. Marek and R. Filip, *Coherent-state phase concentration by quantum probabilistic amplification,* Phys. Rev. A **81**, 022302 (2010).

Reported progress towards Deliverable 1.6:
Detector process tomography
(Partner POTSDAM)

Detectors are the windows to the quantum world, and understanding a detector essentially amounts to understanding how accurately the envisioned experiment could have been performed. In the first year, partner POTSDAM reported a major progress on this topic with the first experimental realization of a full detector tomography, published in Nature Physics in 2009 (the experiment was realized in the group of Prof. I. A. Walmsley).

In this second reporting period, we have continued and significantly further developed our work on detector tomography, the idea of measuring the functioning of a quantum detector without having to make any - possibly unjustified - a priori assumptions about the detector. This work has now been extended to cover weak instances of homodyning, so detectors with both having photon number resolution and a phase reference, hence combining the best of both worlds. The techniques developed for detectors have in particular now been used to quantify entanglement in continuous-variable distillation schemes, without having to make assumptions about the character of the measured state [1]. This deliverable is now completed, even though the work is ongoing - in particular with applications in precise quantum state manipulation - and more results may follow.



Publications:

[1] G. Puentes, A. Datta, A. Feito, J. Eisert, M.B. Plenio, I.A. Walmsley, *Entanglement quantification from incomplete measurements: Applications using photon-number resolving weak homodyne detectors*, New J. Phys. **12**, 033042 (2010).

Workpackage 2: Design of atomic components of CV quantum computing

Period covered: from 01/04/09 to 31/03/10
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 2 of the project

Partner NBI made important steps in optimization of the performance of an atomic memory formed by a cloud of cold Cs atoms that can be used for precision metrology and for preparation of non-Gaussian states of atomic ensemble. The technical noise induced by a microwave reference oscillator was suppressed by constructing a low phase noise microwave synthesizer chain. A tomography microwave pulse sequence was developed that is robust against coupling inhomogeneities and can be used for complete characterization of atomic memory state. A full squeezing-enhanced atomic clock protocol was implemented that over short integration time performs better by 1.1 dB compared to standard Ramsey spectroscopy. The high phase sensitivity of atomic ensemble makes preparation of phase sensitive atomic states such as cat states a formidable task. To resolve this problem it was decided to reduce phase sensitivity by using much fewer atoms trapped along a nanofiber. In parallel, the current setup was modified to enable creation of atomic Fock states following the DLCZ scheme.

Partner NBI also successfully continued experimental exploration of quantum memory formed by ensembles of hot atoms held in a glass cell. A refined theoretical model of atoms-light coupling taking into account tensor terms in the interaction Hamiltonian enabled more effective optimization of the memory protocol. Pre-squeezing of the atomic state was used to decrease the noise in quantum storage scheme. Storage of entangled two-mode squeezed states of light was successfully demonstrated outperforming any possible classical memory scheme. Partner CNRS/ENS performed a detailed study of light storage in Cs vapor by the process of electromagnetically induced transparency. It was shown that due to complicated internal level structure of Cesium, the inhomogeneous broadening can be very detrimental for memory operation. This negative effect can be suppressed by two orders of magnitude by cooling the atoms and an effective cooling mechanism through an engineered optical pumping was proposed for this purpose. In parallel, a new setup for experiments with cold atomic ensembles in MOT has been developed.

Partner MPG investigated protection of state stored in a quantum memory from depolarizing noise. It was shown that using so-called protecting Hamiltonians the lifetime can increase at most logarithmically in the number of atoms composing the memory. Partner UP proposed a scheme for Gaussification of states of light in atomic memory which can be used for preparation of arbitrary Gaussian state in atomic memory or for entanglement purification of non-Gaussian states of light followed by direct storage of purified state in an atomic quantum memory. Partner USTAN suggested and analyzed a scheme for concentration of entanglement of two atomic ensembles via their local QND interaction with light followed by photon counting detection on light. Partner USTAN also proposed a scheme for generation of atomic and hybrid atoms-light CV cluster stares. Partner UP developed a scheme for faithful transfer of a quantum state between two quantum systems under low interaction coupling and a limited controllability of the target system. This method may enable high-fidelity storage in a quantum memory under the presence of various limiting factors. Partner MPG proposed a protocol for generation of quantum superposition states of dielectric objects levitating in a high-finesse optical cavity. The object interacts with a single-photon pulse via Kerr interaction and the light field reflected off the cavity is measured. This procedure can be easily translated to the interaction of atomic ensembles with light. The Kerr coupling was explored also by partner CNRS/IO who generated squeezed states of light using the cross-Kerr effect that arises in an atomic vapor excited close to resonance. Substantial amount of squeezing up to 1.4 dB was obtained. The squeezed light is generated at frequency close to D1 line of 85Rb, and is thus suitable for storage in Rb vapor.

Finally, COMPAS members developed during the second year of the project several novel and promising CV quantum repeater architectures. Partners NBI and DTU proposed a quantum repeater based on non-Gaussian cat-like states which exploits the advantages of highly efficient homodyne detection. A full performance of the protocol was evaluated taking into account imperfections inherent in the scheme. It was found that the protocol is comparable to best theoretical proposals for discrete variable repeaters and will outperform the discrete variable protocol for realistic photo detection efficiencies. Partners CNRS/IO and CNRS/ENS analyzed in detail a scheme for the remote preparation of entangled coherent states by photon counting, and showed that entanglement can be created over 10 km long elementary links .Partner CNRS/ENS proposed a quantum repeater architecture based on entangled coherent states that can be prepared remotely by subtracting non-locally a single photon from two quantum superpositions of coherent states. The entanglement generation rate of this scheme is comparable to that of repeaters based on single-photon entanglement. Partner MPG proposed a versatile setup consisting of an array of cavities and passive optical elements, which allows for quantum state engineering, purification, and non-destructive number resolving photon detection. This protocol can be easily adapted to a communication scenario for purification of photon-number correlated states after transmission to distant parties so that entanglement can be distributed and purified in a network.

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

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.

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

Status: Due month 36; Intermediate progress reported (in progress).

Partners: NBI, MPG

Reported progress towards Deliverable 2.1:

Engineering and manipulating states of an atomic quantum memory
(Partner NBI)

One of the objectives of Task 2.1 is the demonstration of non-Gaussian states in an ensemble of cold atoms. We proposed to achieve this goal by performing a two step process: Light interacts with an atomic ensemble, becomes entangled with the atoms and a subsequent measurement on the light then projects the atoms into a quantum state dependent of the measurement outcome.

Last year we demonstrated how to use this technique to generate an entangled state - a spin-squeezed state - by performing quantum-non-demolition (QND) measurements on an optically dense cloud of 10^5 cold cesium atoms. To obtain a strong coupling between light and an atomic ensemble a high optical density is required. We achieve this strong coupling by trapping a relatively large number of atoms in pencil-shaped dipole trap.

Spin squeezed states of many atoms are of great interest in precision metrology: We achieved a degree of squeezing that in principle would allow for an improvement of the precision of an atomic clock by >3 dB. In June 2009 this work was published in the Proceedings of the National Academy of Science [1]. In 2009 our work was targeted towards using and manipulating the entangled state to actually perform a clock measurement beyond the projection noise limit.

We learned that especially on short time scales the precision of our atomic clock exceeded that of our microwave reference oscillator by orders of magnitude, therefore adding a large amount of technical noise to the phase quadrature of our entangled state. So a key step in the implementation of the squeezing augmented clock sequence was the construction of a low phase-noise microwave synthesizer chain: A dielectric resonator oscillator is phase-locked to an oven stabilized quartz oscillator which itself is slowly referenced to the atomic clocks of the Global Positioning System (GPS). By combining this oscillator with a direct digital synthesis (DDS) board we now can shape our microwave pulses with a precise timing of 4 ns steps and control their phase digitally and precisely.

With this source we then systematically investigated the influence of inhomogeneous microwave coupling and took first steps towards a quantum-tomographic analysis of the spin squeezed state that we prepared. We developed a tomography microwave pulse sequence that is robust against to coupling inhomogeneities and improved our bichromatic QND measurements [1] by changing the interferometer configuration [2,3] that is used to dispersively probe the atomic populations in the clock levels.

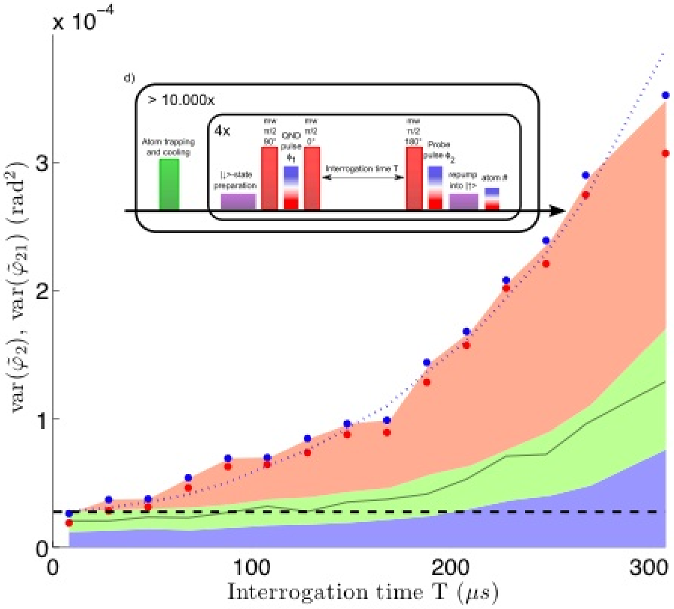


Figure 1: *Atomic clock beyond the projection noise limit. Inset: Pulse sequence: Atoms are cooled and trapped in a dipole trap and prepared in one of the clock states. Microwave pulses (dark red bars) and bichromatic optical pulses (red-blue-bars) are then used to perform a modified Ramsey spectroscopy sequence. Main Figure: Atomic phase fluctuations vs. interrogation time. Blue area: Light noise contributions. Green area: Atomic projection noise. Red area: Classical noise sources. Blue dots: Phase fluctuations of a conventionally operated atomic clock. Red dots: Phase fluctuations with spin squeezing: Black line: Threshold for entanglement. For details see [4]*

Finally we developed a modified Ramsey-sequence to measure the atomic transition frequency and implemented a full clock-protocol that takes advantage of the reduced projection noise that spin-squeezing can provide: Over a short integration time the squeezing enhanced atomic clock performs better by 1.1 dB compared to using standard Ramsey spectroscopy [4]. While we can control the state of the atoms to a high precision during an experimental cycle (which is important for quantum information applications) with increasing interrogation times our clock becomes precise enough so that we can resolve fluctuations of the clock-transition frequency by 7.5 Hz between successive experimental cycles that are 5 s apart. We attribute this technical noise to instabilities in the trapping potentials and to instabilities of the magnetic fields.

Although in a quantum-memory setting low-frequency components of these technical noises in principle could be eliminated by spin-echo-techniques, the large number of atoms and the associated excellent phase-resolution poses high demands on the control of the environment, which makes the preparation of phase-sensitive atomic states (such as Schrödinger-cat-states) a formidable challenge. We therefore initiated collaboration with the group of A. Rauschenbeutel and plan to achieve stronger light-atom-coupling using much fewer atoms by building a new vacuum setup to trap atoms along a nanofiber [5]. In parallel, in the existing setup we implemented the changes 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. Projection noise limited two-photon microwave-radiofrequency Rabi-pulses have been realized and filtering cavities to separate excitation light pulses from spontaneously emitted single photons have been constructed.

In addition to the experimental work the team at NBI has also done theoretical work on a new approach to multimode atomic operations [6]. In most protocols for processing information in atomic memories, the quantum states stored in two different memories are assumed to be merged by mapping the states onto light, and then, e.g., mixing the light on a beam splitter. In practice, however, the process of reading out the information has a very limited efficiency. The idea in the new work is therefore to avoid the readout process and rely on processing the information inside the atoms. The proposal exploits the fact that, atoms typically have several stable ground states, and not only the two stable ground states, which are normally being assumed. For the Cs atoms used in the experiments at NBI, there are in fact 16 stable ground states. Instead of storing a single mode, these atoms can therefore store a total of 15 modes. A particular advantage of this approach is that, e.g., a beam splitter operation between two modes can be done by simply applying a $\pi/2$ pulse between two levels in the atoms. We have shown how to generate non-Gaussian states in several modes in such a configuration. These non-Gaussian states can later be extended to a full scale quantum repeater, using either continuous or discrete variable techniques. Since the repeater protocols are better established and simpler to analyze in the discrete variable situation, we chose to first analyze the performance of this idea for a repeater protocol in the context of discrete variables. The idea is, however, also applicable to continuous variables. In particular this method constitutes a promising method to realize the repeater protocol described in D2.5, and this represents a possible route forward for the experiments at NBI in the future. An attractive feature in this connection is that the repeater protocol relies on performing homodyne measurements. Using this new approach to multimode memories, the repeater protocol could therefore be implemented by using the homodyne measurement on atoms, which has already been developed in the laboratories at NBI. This approach can thus eliminate the need to retrieve the information onto light.

Publications:

1. J. Appel, P. J. Windpassinger, D. Oblak, U. B. Hoff, and N. Kjærgaard, Proc. Natl. Acad. Sci. 106, 10960 (2009).
2. P. J. Windpassinger et al., J. Mod. Opt. 56, 1993 (2009).
3. M. Saffman, D. Oblak, J. Appel, and E. S. Polzik, Phys. Rev. A 79, 023831 (2009).
4. A. Louchet-Chauvet et al., accepted by New. J. Phys. (2010), in print.
5. E. Vetsch et al., Optical interface created by laser-cooled atoms trapped in the evanescent field surrounding an optical nanofiber, 2009.
6. Jonatan B. Brask, Liang Jiang, Alexey V. Gorshkov, Vladan Vuletic, Anders S. Sørensen, and Mikhail D. Lukin, Fast Entanglement Distribution with Atomic Ensembles and Fluorescent Detection, Phys. Rev. A 81, 020303(R) (2010).

Reported progress towards Deliverable 2.1:

Engineering and manipulating states of an atomic quantum memory
(Partner MPG)

Reliable storage of information in quantum memories is very important for many applications in quantum information processing, but hampered by adversary effects of the environment. Using so-called protecting Hamiltonians, which permanently act on the quantum memory, it can be immunized against small perturbations. This approach is attractive, as it does not require any active action on the quantum memory. It is known that protecting Hamiltonians tolerate certain types of perturbations, but it is unclear whether it is suitable in the presence of depolarizing noise, which is an important factor in practical applications. In this work, a complete answer to this question is given.

In the absence of a protecting Hamiltonian, the lifetime of a single qubit exposed to depolarizing noise is independent of N, the number of atoms composing the memory. It s established that in the presence of a protecting Hamiltonian, the lifetime can increase at most logarithmically in N. Moreover, a time independent Hamiltonian is constructed, which saturates this bound. Remarkably, noise itself is used to achieve this protection.

Publication:

F. Pastawski, A. Kay, N. Schuch, and I. Cirac, "*How long can a quantum memory withstand depolarizing noise?*", Phys Rev. Lett. 103, 080501 (2009).

Conference presentations:

- Symposium on Topological Quantum Information, Leeds, UK, April 11-12, 2010 [TALK]
- QIP 2010, 13th International Workshop on Quantum Information Processing, Zürich, Switzerland, January 18 - 22, 2010. [POSTER]
- Benasque Workshop on Quantum Information Science, Benasque, Spain, June, 7-28, 2009. [TALK]

Reported progress towards Deliverable 2.1:
Gaussification of quantum states of traveling light beams in atomic memory
(Partner UP)

Partner UP proposed and investigated a protocol for Gaussification of quantum states of traveling light beams in an atomic quantum memory that couples to light via continuous-variable quantum non-demolition (QND) interaction. The Gaussification operation produces in the atomic memory a state whose quadrature operators are balanced superpositions of quadratures of all M input light modes. The scheme can be used to prepare entangled states of two distant atomic ensembles and to purify and Gaussify noisy non-Gaussian entangled states of light while simultaneously storing the purified state in a pair of distant atomic memories.

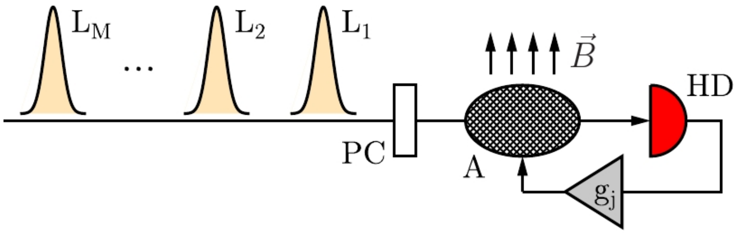


Figure. 1: *Proposed scheme for Gaussification of quantum states of M propagating light modes in atomic quantum memory. Each light beam (Lj) interacts with an atomic ensemble (A) and is measured by homodyne detector (HD). The atomic state is then displaced by an amount proportional to the measurement outcome. The QND interaction between light and atoms is periodically switched with the help of a fast polarization controller (PC) and magnetic field pulses (B).*

The protocol involves repeated switching between two different quantum non-demolition couplings, homodyne detection of output light and feedback on atoms, see Fig. 1. At each step, the value of the coupling constant is properly adjusted by controlling the intensity of the auxiliary strong coherent laser beam. An important feature of the suggested scheme is that it does not require any pre-squeezing of the atomic memory and the total QND coupling strength scales only logarithmically with number of Gaussified light modes. This is important because certain decoherence effects in the atomic memory are proportional to the total coupling strength. Another appealing feature of the suggested scheme is that the light beams need not be perfectly synchronized and can arrive at different times.

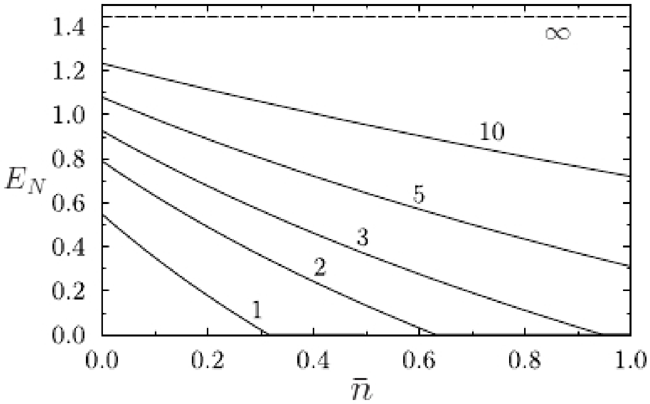


Figure 2: *Entanglement of two atomic ensembles created by local mappings of parts of pure two-mode squeezed vacuum onto the atomic memories. The logarithmic negativity of the two-mode atomic state is plotted as a function of the initial mean number of thermal quanta in the memory. This dependence is shown for several number of Gaussification steps M = {1, 2, 3, 5, 10}. The dashed line indicates the maximum entanglement achievable in the asymptotic limit M → ∞.*

If the Gaussification protocol is applied to light beams prepared in identical independent Gaussian states with covariance matrix γ_L and zero displacement, then the protocol asymptotically maps the Gaussian state of light into atomic memory, i.e. in the limit M → ∞ the atomic memory is prepared in a Gaussian state with covariance matrix $\gamma_{L.}$ This procedure can be used to establish entanglement between two distant atomic quantum memories by mapping parts of an entangled state of light into them. The Gaussification procedure is applied locally to each atomic memory and sequence of light modes. The entanglement of two memories established after M steps of local Gaussifications of two-mode squeezed vacuum states of light is plotted in Fig. 2.

Since all components of the proposed scheme have already been successfully experimentally demonstrated in the recent years a small-scale demonstrations with M = 2 or M = 3 is feasible with present-day technology. If combined with conditioning on the outcomes of homodyne detection on output light, the present protocol can be used to purify and Gaussify non-Gaussian mixed entangled states.

Publications:

J. Fiurášek, *Gaussification of quantum states of traveling light beams in atomic memory,* submitted to Phys. Rev. A (2010).

Reported progress towards Deliverable 2.1:
An Entanglement Concentration Protocol for two Atomic Ensembles
(Partner USTAN)

The most promising protocol so far for potential use in Quantum Repeaters is that shown by Julsgaard *et al.* [1] using the coherent spin states of caesium atoms to serve as a memory device. The quantum signal to be transmitted is contained in the polarisation state of the strongly polarised incoming light mode, and characterised by the quantum Stokes operators. Due to the strong polarisation of the light conjugate position and momentum operators can be defined. This signal is written onto the macroscopic coherent spin state of the atomic ensemble. Julsgaard *et al* successfully showed that the coherent spin states of two atomic ensembles could become entangled in such a way as to be analogous to the two mode squeezed state for light. The better entangled the ensembles, the better the outcome of the quantum repeater protocol. Unfortunately, the entanglement of two atomic ensembles is at present far from perfect with experimental teleportation fidelities of <0.6. Over the past year, Partner USTAN has strived to find a way of increasing the entanglement between two atomic ensembles.

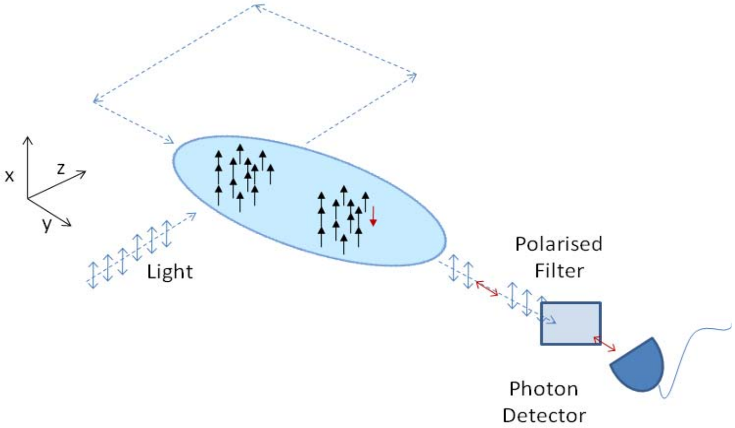


Fig 1: Light is strongly polarised in the x direction. It interacts with the atomic ensembles twice and a y polarised photon detection implies entanglement has increased.

Due to the polarisation of the atoms, atomic quadratures can also be defined. We can then send polarised light pulses to the atomic ensembles and rewrite the linearised dipole interaction as a quantum non-demolition Hamiltonian. If the light pulse weakly interacts twice with the atomic ensemble via QND interactions, then it is shown that the quadrature evolution for light and atoms is similar to the evolution seen in beam-splitter transformations. The outgoing light mode is sent through a polarised filter to cancel out the background beam of x-polarised photons and any remaining photons are detected at a photon detector, see Fig. 1. If, after the beam-splitter-like interaction, one or more photons are detected behind the polarised filter, then the interaction has rotated the polarisation of some photons in the light mode. The corresponding back action on the atomic ensembles is to flip the spin of one or more of the atoms in the system. We show that if this interaction and detection is successful on both ensembles, then the entanglement of the ensembles increases (Fig. 2). The probabilities of success are comparable to those of the light scheme for which this is analogous [2].

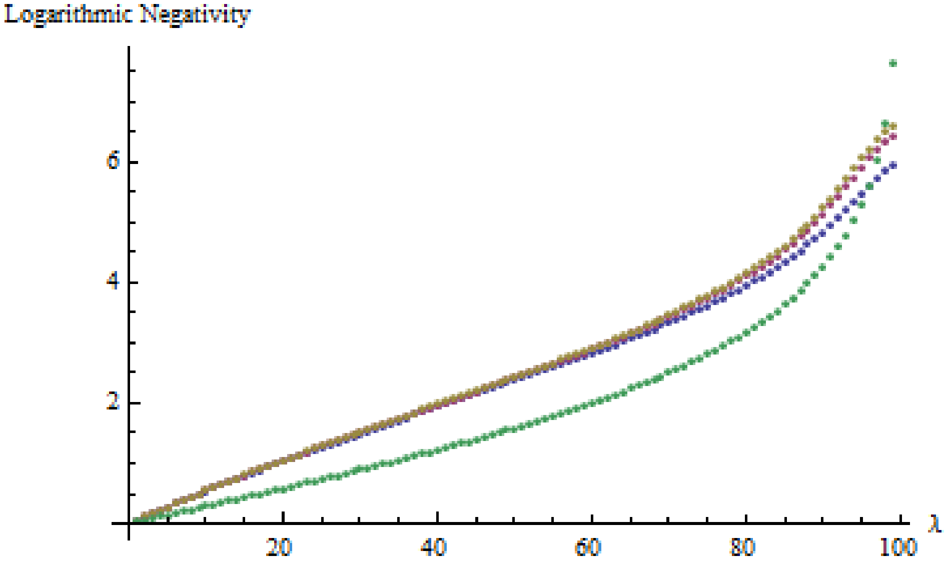


Fig 2. A plot of the logarithmic negativity against initial atomic squeezing λ for (i) standard two mode squeezed state (green) and the photon subtracted scheme for the beam-splitter like interaction between light and atomic ensemble when (ii) interaction strength φ =0.1 (blue), (iii) φ =0.05 (red), and (iv) φ =0.01 (yellow). The entanglement concentration increases as φ decreases for λ values approaching 0.95.

References

[1] B. Julsgaard, A. Kozhekin, and E. Polzik, Nature, **413,** 403 (2001).
[2] A. Kitagawa, M. Takeoka, M. Sasaki, and A. Chefles, Phys. Rev. A, **73**: 042310 (2006).

Conference Poster Presentations

- 16th Central European Workshop on Quantum Optics (CEWQO), May 2009
- 11th International Conference on Squeezed States and Uncertainty Relations (ICSSUR), June 2009
- Summer School on Scalable Quantum Computing with Light and Atoms, August 2009

Reported progress towards Deliverable 2.1:

Generation of Continuous Variable Atomic and Hybrid Cluster States with QND Measurements.
(Partner USTAN)

Cluster states are a class of multipartite entangled state that have been shown to be a resource for universal one-way quantum computation [1]. These states have attracted much attention in the last few years and many optical implementations, where the clusters are constructed from modes of light, have been suggested and experimentally verified [3]. However, to make any quantum computation on cluster states universal either a non-gaussian input state must be used or a non-gaussian measurement must be performed. These operations are difficult to perform in the optical regime so here we propose a protocol for the generation of cluster states between ensembles of atoms. We have also shown that we can create clusters between these atomic ensembles and light modes in a so called *Hybrid* cluster state. These protocols both make use of Quantum non-demolition (QND) interactions between light and atoms in a way reminiscent of the quantum memory protocol of Julsgaard *et al* [2]. Due to the wider range of interactions available on atomic systems we believe that it will be possible to enact non-gaussian measurements on the ensembles and hence achieve universality.

In our scheme we will assume that all the atoms are polarized along one direction which we denote the x-axis. This allows us to treat the x-component of the collective spin as a classical number and so we can replace the spin operators in the x direction by classical numbers. The transverse spin components y and z maintain their quantum nature. They will typically have zero or a small mean value. This allows us to define new spin variables that satisfy a position/momentum like commutation relation. Similarly, consider a pulse of light, or a collection of photons, propagating in the z-direction. The polarization state is well described by the Stokes operators. We assume that the photons are linearly polarized along the x-direction which allow us to treat the x component Stokes operator as a classical number just as we did with the atoms. So we can define new quantum variables and we see that, just like the atomic spins, the polarization states are similar to the standard position/momentum operators.

To construct our cluster state we must ensure that certain conditions are met. The state we aim to produce must be a simultaneous eigenstate of particular quadrature combinations. To achieve this we use QND interactions to encode the required linear combinations onto each atomic ensemble then use a further QND measurement on each ensemble to read these out and hence reduce the variance to zero. We build up the correct linear relations on a particular node, i, by interacting a light pulse via a QND Hamiltonian with all its neighbours, j. This picks up the spin information from each of the neighbouring ensembles and stores it in the polarization of the light pulse. This pulse can then be passed through ensemble i where it interacts according to another QND Hamiltonian which encodes the polarization state and hence the picked up atomic spin- state from the neighbouring ensembles in ensemble i. This procedure is repeated for each node by a sequence of light pulses in turn but we note that for each one added we pick up extra noise from the back action of the light. We construct Hybrid clusters in a similar fashion but with the addition of beamsplitters to perform light/light interactions. These protocols both pick up a certain amount of noise from the back action of the entangling light pulses but this can be reduced by squeezing and careful choice of the QND coupling constants.

References

[1] N. C. Menicucci, P. Van Loock, M. Gu, C. Weedbrook, T. C. Ralph and M. A. Nielsen, 'Universal Quantum Computation with Continuous Variable Cluster States,' Phys. Rev. Lett **97**, 110501 (2006)
[2] B. Julsgaard, A. Kozhekin and E. Polzik, Nature, Vol **413**, (27 Sept 2001)
[3] M. Yukawa, R. Ukai, P. Van Loock and A. Furusawa 'Experimental generation of four-mode continuous variable cluster states' Phys. Rev A **78**, 012301 (2008)

Conference Poster Presentations

- 16th Central European Workshop on Quantum Optics (CEWQO), May 2009.
- 11th International Conference on Squeezed States and Uncertainty Relations (ICSSUR), June 2009.
- Summer School on Scalable Quantum Computing with Light and Atoms, August 2009.

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

The goal of this task was to investigate and experimentally 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 were planned to be developed based on the off-resonant interaction of light with cold Cesium atoms held in a magneto-optic trap.

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

Status: Due month 24; Delivered; Additional progress expected at the end of the third period.

Partners: NBI, CNRS/ENS.

Reported progress towards Deliverable 2.2:

Light-atoms quantum interface for quantum information processing
(Partner NBI)

An experiment on quantum memory for displaced squeezed states was conducted. The protocol relies on the dispersive interaction of two polarized Caesium ensembles at room temperature, each containing around 10^{12} atoms. It is based on a measurement and feedback scheme, where the light, which is to be mapped, first interacts with the ensembles after which a measurement is conducted on the light. The measurement results are fed back to the atomic ensembles, thus completing the mapping.

The original procedure of this mapping protocol was improved twofold. Firstly, the spins of the atomic ensembles were entangled prior to the mapping experiment, to minimize the residual input noise from the atoms, which spoils the performance of the memory.
Also, a deeper understanding of the underlying interaction, which forms the foundation of the atom light interface helped in optimizing the protocol. This newly developed extension of the theory is based on the inclusion of higher order terms (tensor terms) from the Hamiltonian in the description of the interaction. As a result, new possibilities for interesting experiments, as for example engineering of two mode squeezed light, arise. Such a measurement was conducted successfully and is described together with the extended theory in [1]. Also the new understandings lead the way to optimize the quantum memory more effectively.
With the new improved protocol an experiment was conducted, mapping different displaced squeezed states, outperforming any possible classical memory scheme for a certain class of states [2].

In figure 1, a schematic picture of the experimental setup is shown. After the preparation of the two atomic states in an entangled state, the squeezed light, produced with standard OPO techniques, is sent through the atomic ensembles. The light hits the detectors and the feedback of the measurement outcomes finalizes the mapping.

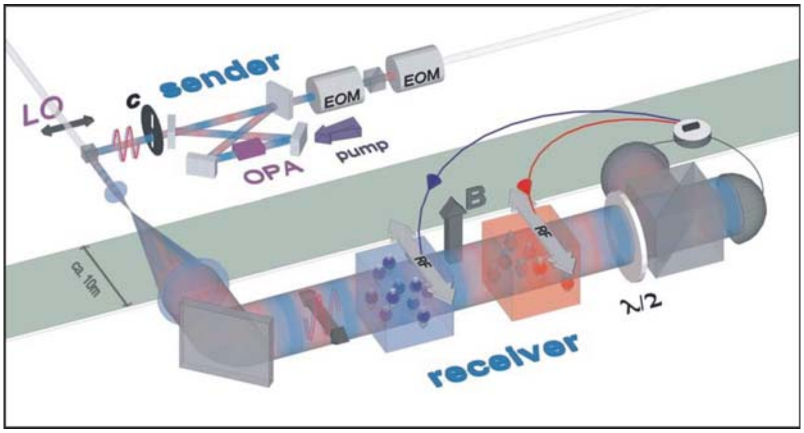


Figure 1: *Setup for quantum memory of squeezed states*

Publications:

1. W. Wasilewski, T. Fernholz, K. Jensen, L. S. Madsen, H. Krauter, C. Muschik, and E. S. Polzik, Generation of two-mode squeezed and entangled light in a single temporal and spatial mode, Optics Express, 17, 14444 (2009)
2. K. Jensen, W. Wasilewski, H. Krauter, T. Fernholz, B. M. Nielsen, A. Serafini, M. Owari, M. B. Plenio, M. M. Wolf, E. S. Polzik, Quantum memory for entangled two-mode squeezed states, submitted, arXiv:1002.1920 (2010).

Reported progress towards Deliverable 2.2:

Light-atoms quantum interface for quantum information processing
(Partner CNRS/ENS)

A realization of a light atom quantum interface had been presented by partner CNRS/ENS at the end of the first period (Phys. Rev. Lett. 101, 133601). Systems with improved characteristics are under study presently, as detailed below, and will be delivered at the end of the third period.

Quantum storage was demonstrated in the first period using a three-level adiabatic passage protocol implemented on cesium vapour in a cell. Two non commuting variables of light, i.e; two quadratures, were stored in the atomic coherence of the ground state. A detailed study of the light atom interface processes that are at the basis of quantum storage in cesium vapour has been performed during the second period in order to improve the storage efficiency. On the other hand a system involving ultra-cold atomic ensembles has been set up and is presently under test for improved performances (fidelity and memory time). These two approaches are detailed in what follows:

1) *Improvement of the quantum storage efficiency in Cesium vapor*

The quantum memories that are developed in our group are based on Electromagnetically Induced Transparency (EIT). The coherent interface between the input light signal and matter is achieved by dynamically controlling a strong resonant control field. As the signal field propagates through the atomic medium, the group velocity is adiabatically reduced to zero, the quantum state being converted from a purely photonic state to a matter-like collective spin coherence. When the control field is reactivated, after a user-defined delay, the collective spin is coherently converted back into a photonic mode in a time-reversed fashion. Using this technique, our group has demonstrated the storage and retrieval of small coherent states, in a warm vapor of cesium atoms.

To characterize the storage characteristics in a universal way (i.e. independent of the sate being stored), we have used the T-V criterion, that allows to define the borders of the quantum domain as long as the transfer efficiency between the initial signal and the retrieved field and the conditional variances are known. This detailed study confirms the quantum character of our storage [1].

However, due to the hyperfine structure of the upper level of the D2 transition of cesium used in the experiment, we have shown that the EIT behavior is very different from what it is in a simple Lambda system. When the hyperfine structure in the upper state is of the order of the inhomogeneous broadening the EIT characteristics can be very different from those of a 3-level atom. Using a detailed analytical modeling together with numerical simulations, we have studied the dependence of this effect as a function of the inhomogeneous broadening, and we have shown that is can be very detrimental for hot vapors, while it is weak for cold atoms. The induced transparency can be decreased by one to two orders of magnitude [2]. To improve the EIT in vapors, we have proposed an effective cooling mechanism through an engineered optical pumping. The predicted effect has been experimentally demonstrated, with an improvement of the transparency by a factor of about 5. An article is in preparation on this result.

With an enhanced transparency of the atomic vapour, the efficiency of the atomic storage is expected to be increased and this effect is currently being tested.

2) *Light atom quantum interface in ultra-cold ensembles*

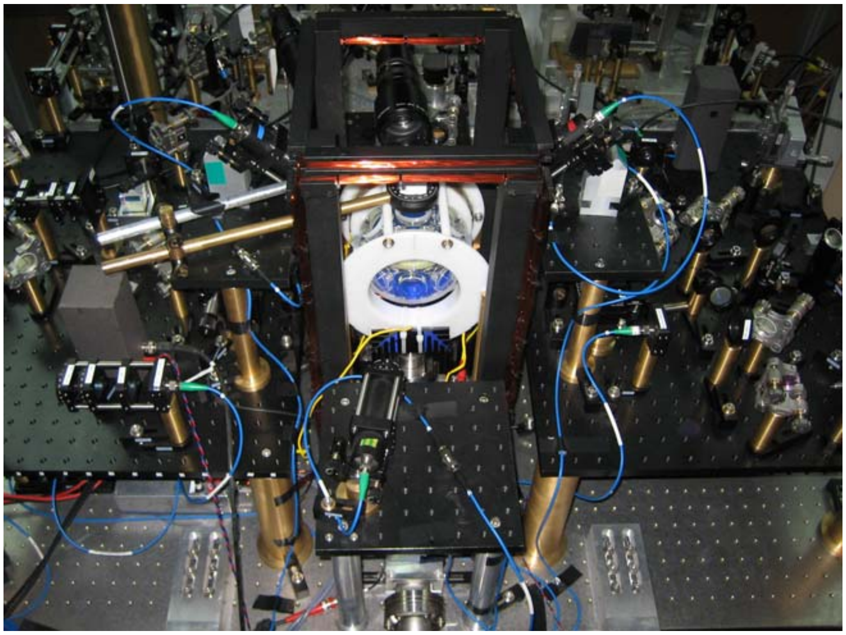


Figure. 1: *Experimental set-up for ultra-cold atoms*

The next step of the experiment will be carried out with cold atomic ensembles. For this, a new ultra-cold atom trap has been set up in order to obtain a high optical depth and to improve the residual magnetic field cancellation, which will optimize the retrieval efficiency and the storage time (Fig.1). The current setup involves a glass chamber, which eliminates Eddy currents (Fig.2). The magnetic field can be turned off in a very short time to allow memory operation. The optimization of the cancellation of the residual magnetic field has been performed. With the present configuration, the atoms being trapped in a MOT and the magnetic field turned off in a very short time, we will be able to implement the adiabatic passage memory protocol and to take advantage of the absence of motion of the atoms to store the light mode very efficiently, while minimizing the decoherence. The storage characteristics in the ultra-cold atomic cloud will be assessed and optimized with a faint coherent pulse within a few weeks.

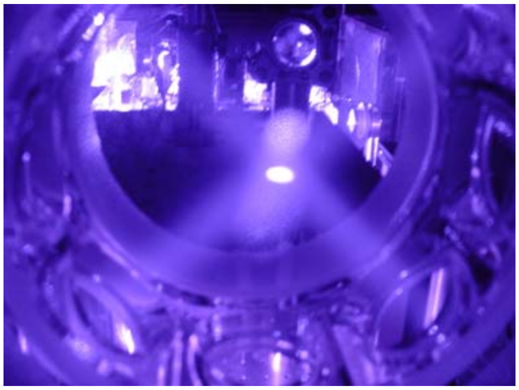


Figure 2. *The MOT in the glass cell and the trapping beams*

The squeezed light modes prepared as described in period 1 will then be transferred into the atomic ensemble and mapped back into a photonic mode after a user-defined delay. The characteristics of storage and retrieval will be studied as a function of the trap parameters.

We have also performed a dynamical study of quantum memories using an oscillator-cavity model in order to be able to engineer the pulse shapes and optimize the output signal. The temporal switching or gating of the device may either be through a control field changing the coupling, or through a variable detuning approach. An exact calculation of the temporal memory response to an external input has been carried out. This shows that there is a mode-matching criterion which determines the optimum input and output mode shape. This optimum pulse shape can be modified by changing the gate characteristics. In addition, we have shown that there is a critical coupling between the atoms and the cavity that allows high fidelity together with long storage times [3]. These results will be applied in the above experiment for the optimization of the storage.

Publications

[1] *Atomic-ensemble-based quantum memory for sideband modulations*, J. Ortalo, J. Cviklinski, P. Lombardi, J. Laurat, A. Bramati, M. Pinard, E. Giacobino, J. Phys. B 42, 114010 (2009)

[2] *Electromagnetically induced transparency in a Lambda-system with several exited states*, O.S. Mishina, P. Lombardi, J. Ortalo, M. Scherman, A.S. Sheremet, D.V. Kupriyanov J. Laurat, E. Giacobino preprint

[3] *Dynamical oscillator-cavity model for quantum memories*, Q. Y. He, M. D. Reid, E. Giacobino, J. Cviklinski, and P. D Drummond, Phys. Rev. A 79, 022310 (2009)

Conference presentations:

- *Russian French German Laser Symposium RFGLS2009* (Nijni-Novgorod, Russie, mai 2009) « Quantum memories for information networks » E. Giacobino, invited conference.
- *Colloque franco-brésilien Nanomagnétisme, Electronqiue de spin et Optique quantique NEOQ2009* (Rio de Janeiro, Brésil, 11-13 Nov 2009) « Quantum state of light storage in atomic media » E. Giacobino, invited conference.
- *1st International ICST Conference on Quantum Communication and Quantum Networking* (Naples, october 2009), "Matter-matter entanglement for quantum communication", J. Laurat, invited conference

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Reported progress towards Deliverable 2.2:

Noise resilient quantum interface
(Partner UP)

Partner UP studied how an unknown quantum state can be faithfully transferred between two quantum systems under the presence of two limiting factors. These factors are a low strength of the interaction coupling the two quantum systems together and a limited controllability of the system the quantum state should be transferred to. These limitations are not arbitrary, in fact they naturally occur when light interacts with some other physical system, such as an atomic cloud.

It was shown that for a Gaussian coupling of arbitrary strength an unknown quantum state can be perfectly and deterministically transferred to the target quantum system, provided we have access to a suitable all-optical pre processing involving ancillary light modes. This transfer requires only a limited manipulation of the target system consisting solely of displacement operations, and works without any regard for the initial state of the target system. For example, for the attenuation type coupling the required pre-processing is in the form of a two-mode squeezer and the transfer is completed by performing a joint measurement of the ancilla and the signal after the interaction and a feed-forward.

There is one exception, however. A single asymmetrical QND type coupling cannot be used in this way. Nevertheless, it was shown that two of those are already sufficient, with pre-processing in the form of another QND interaction and with a feed-forward which does not even need the joint measurement.

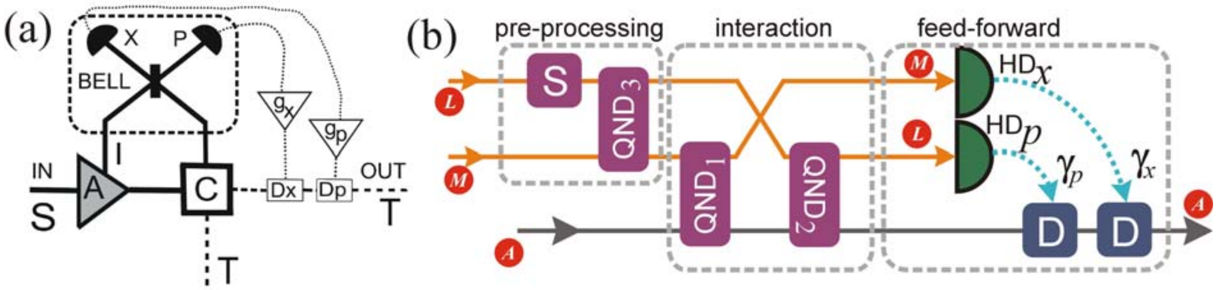


Fig. 1: *(a) Schematic setup of interface through an attenuation coupling. C - attenuation coupling, A - two-mode squeezer, S - light signal, I - light ancilla, T - target system, Dx Dp - displacement operations. (b) Schematic setup of interface through a QND coupling. S - single mode squeezing, L - light signal, M - light ancilla, A - target system, HD - homodyne detection, D - displacement operation*

Publications:

R. Filip, *Quantum interface to a noisy system through a single kind of arbitrary Gaussian coupling with limited interaction strength,* Phys. Rev. A **80**, 022304 (2009).

P. Marek, R. Filip, *Noise-resilient quantum interface based on quantum nondemolition interactions,* Phys. Rev. A **81,** 042325 (2010).

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

The objective of this task was to explore novel effects that may potentially be exploited in order to get a very high nonlinear effect. In particular, the goal was to investigate the cross-Kerr effect that arises in an Electromagnetically Induced Transparency-type interaction of light with an atomic system. Another pursued research avenue consisted 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.

Deliverable2.3: ***Interfacing light with atoms in optical lattices and trapped ions***
Status: Due month 24; Intermediate progress reported in Y1; Delivered.

Deliverable2.4: ***Alternative methods for generating non-Gaussian states using Kerr nonlinearity***
Status: Due month 24; Intermediate progress reported in Y1; Delivered.

Partners: MPG, USTAN, CNRS/IO

Reported progress towards Deliverable 2.3

Interfacing light with atoms in optical lattices and trapped ions
(Partner MPG)

The work included in the activity report of the first year (Collective generation of quantum states by entangled atoms) was finished, so this deliverable is now complete.

Conference presentation:

- Bose-Einstein Condensation 2009 Frontiers in Quantum Gases, San Feliu den Guixols, Spain, September, 5-11, 2009. [INVITED TALK]

Reported progress towards Deliverable 2.4

Alternative methods for generating non-Gaussian states using Kerr nonlinearity
(Partner MPG)

In this work, three methods are proposed and investigated, which lead to the creation of non-Gaussian quantum superposition states using a Kerr-interaction. Note that this work is presented in the context of dielectrical objects, but the underlying physics and results apply to any system which can be described in terms of bosonic modes and interacts with light according to the Kerr-Hamiltonian. In particular the results can be directly translated to the interaction of atomic ensembles with light.

The proposed protocol is based on non-Gaussian input states of light. A dielectric object is levitated in a high finesse optical cavity by means of optical tweezers (see Fig.1). This mechanical object interacts with the quantum field of light via a Kerr-interaction, which is enhanced by means of a strong driving field applied to the cavity. A suitably devised single photon pulse is partly reflected and partly transmitted into the cavity. The transmitted part leads to mapping of the photonic state onto the mechancal degree of freedom and an entangled state of the mechanical system and the reflected part of the light pulse is created. Hence, a superposition state of the mechanical system can be produced by performing a measurement on the reflected light field.

Alternatively the coupling between light and matter can be modulated, by varying the intensity of a red-detuned driving field, such that any photonic input state pulse enters into the cavity and is perfectly mapped to the mechanical system. Finally, by driving the cavity with a blue-detuned field, a two-mode squeezing state is created between the mechanical system and the output field, which can be used to teleport a non- Gaussian state to the levitated object. This method is also applicable in the bad-cavity limit.

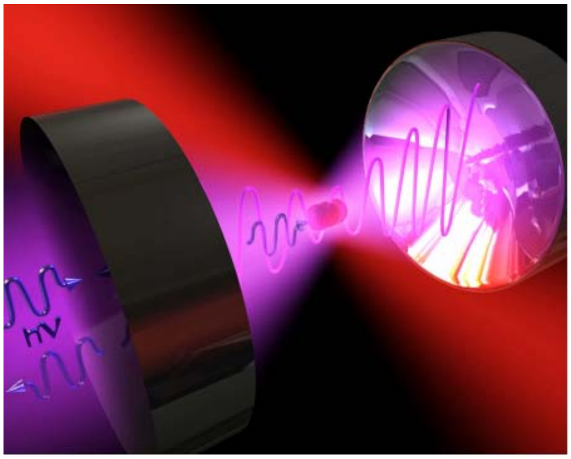


Fig.1: *Illustration of the proposed protocol for creating quantum superposition states of dielectric objects levitated in a high-finesse optical cavity by optical tweezers*.

Publication:

- “Towards Quantum Superposition of Living Organisms”
O. Romero-Isart, M. L. Juan, R. Quidant, and J. I. Cirac
New J. Phys. 12, 033015 (2010).
(Featured in: Economist, Nature News, New Scientist, Physics World, Science Daily.)

Conference presentations:

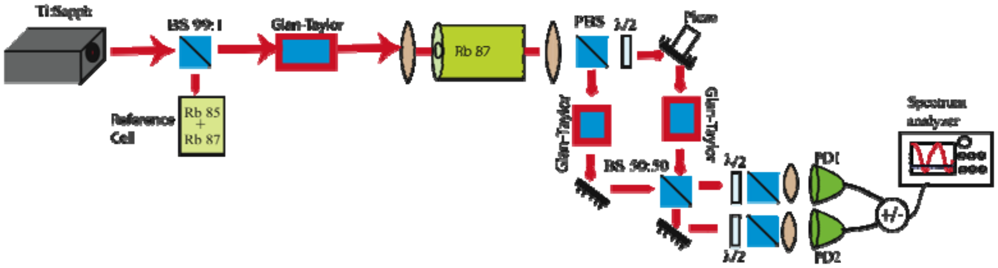
- CREST 2010 International Symposium on Physics of Quantum Technology, Tokyo, Japan, April, 6-9, 2010. [INVITED TALK + POSTER]
- Gordon Research Conference on Mechanical Systems in the Quantum Regime, Galveston, Texas, USA, March, 21-26, 2010. [POSTER]
- International Conference on Quantum Optics, Obergurgl, Tirol, Austria, February, 21-26, 2010. [POSTER]
- QIPC 2009, Rome, Italy, September 21-25, 2009. [INVITED TALK]
- Bose-Einstein Condensation 2009 Frontiers in Quantum Gases, San Feliu den Guixols, Spain, September, 5-11, 2009. [POSTER]
- WE-Heraeus-Seminar on Quantum Optics of Nano-and Micromechanical Systems, Bad Honnef (Bonn), Germany, July, 19-22, 2009. [POSTER]

Reported progress towards Deliverable 2.4

Alternative methods for generating non-Gaussian states using Kerr nonlinearity
(Partner CNRS/IO)

The goal 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 have been investigating the generation of pulsed and continuous-wave squeezed vacuum using the cross-Kerr effect that arises in an atomic vapour excited near resonance because of the nonlinear rotation of the polarisation ellipse.

This approach allowed us to produce squeezed light pulses [1], which may be transformed into non-Gaussian states by using measurement-induced nonlinear operations, as demonstrated in WP1. 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, which are also developed by other groups in COMPAS.



We used a room-temperature cell containing rubidium 87 vapour pumped by a CW Ti:Sapphire laser near the D1 and D2 line, both in continuous wave regime and in the pulsed regime (using an EOM to chop the CW beam into 200 ns pulses). The noise on the polarization orthogonal to the pump polarisation (vacuum field) was monitored using standard optical homodyne detection. While only excess noise was observed around the D2 line, we have been able to obtain substantial amounts of squeezing (up to 1.4 dB) over a wide range of input powers and pump detuning around the D1 line (up to ~1GHz) in the CW regime. Using 200 ns pulses at 1 MHz repletion rate, we demonstrated up to 1dB of squeezing for a pump laser frequency detuning from the D1 line of 87Rb that correspond to resonance on the D1 line of 85Rb, allowing to envision storage of the produced states in 85Rb vapours.

Publications:

[1] : Imad H. Agha, Gaétan Messin, and Philippe Grangier, Opt. Express 18, 4198 (2010).

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; Delivered.

Partners: NBI, MPG, DTU

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
(Partners NBI, DTU)

Partner NBI and DTU has completed a proposal for how one can construct a quantum repeater exploiting the advantages of continuous variables. Quantum repeaters based on atomic ensembles are severely limited by the limited detection efficiency of single photon detectors. The idea in this work is therefore to exploit the superior performance of homodyne detection for more efficient quantum repeaters. The protocol consists of three parts shown in the figure below and is based on techniques either already available or being developed in the NBI laboratories:

1) A non-Gaussian state is generated over long distances by conditioning on the detection of a photon. This part thereby exploits the advantage of discrete variables for transmitting information over long distances.
2) The non-Gaussian states are grown into a large cat-state using homodyne detection. In addition to the advantage of efficient homodyne detection, this protocol is highly efficient for making large cat states, when atomic memories are available. Because it relies on merging a large number of small states, which can be stored in memories, the protocol avoids the fast exponential decrease in the success probability, which is typically present in protocols generating large cat states, relying on simultaneous detection of a large number of photons.
3) The cat states are connected to large distances using homodyne detection. In the simplest version of the protocol it succeeds with a probability of one half, but this can be increased to unity using local cat-states as a resource.

We have evaluated the full performance of the simplest version of the protocol taking into account the imperfections inherent in the protocol. This study shows that in its simplest version, the performance of the protocol is comparable to the best theoretical protocols for discrete variable quantum repeaters based on atomic ensembles. To attain this performance the discrete variable protocols, however, need to assume unrealistically high photo detection efficiencies, and the continuous variable protocol will thus outperform the discrete variable protocol for realistic photo detection efficiencies. Furthermore the performance of the continuous variable repeater may be improved by using the more advanced entanglement swapping protocol.

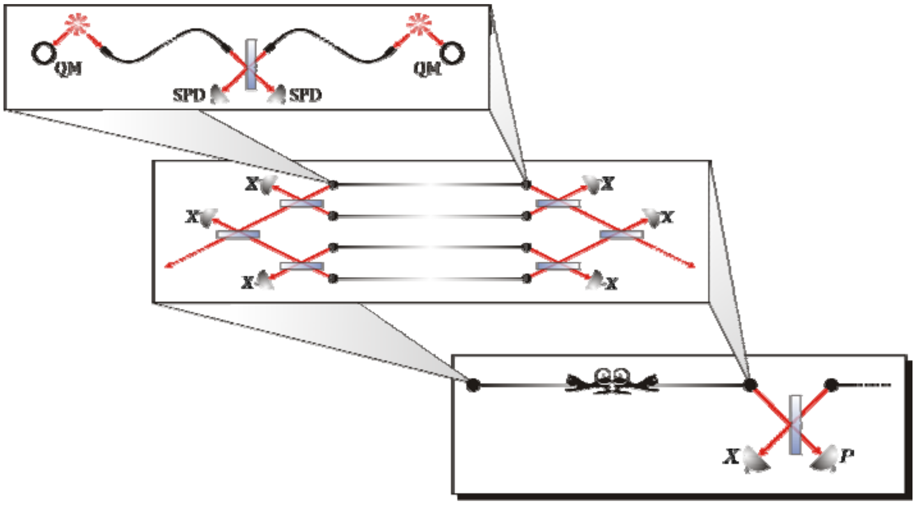


Figure 2: *The three elements of the repeater protocol. First, entanglement is generated non-locally by conditioning on a click in a photo detector. This entanglement is then grown into non-local cats states by homodyne measurements, and finally entanglement swapping is achieved by homodyne detection on the cat states.*

Publications:

Jonatan B. Brask, Ioannes Rigas, Eugene S. Polzik, Ulrik L. Andersen, and Anders S. Sørensen, *A Hybrid Long-Distance Entanglement Distribution Protocol*, article available at arXiv:1004.0083v2 [quant-ph]

Reported progress towards Deliverable 2.5:

CV quantum repeaters based on complex quantum network geometries
(Partner MPG)

In this work, a versatile setup consisting of an array of cavities and passive optical elements (beam splitters and phase shifters) is proposed, which allows for quantum state engineering, quantum state purification, and non-destructive number resolving photon detection. Photon-number correlated states, for example Einstein-Podolsky-Rosen (EPR) entangled states , are an important resource for quantum teleportation, entanglement swapping, quantum key distribution, and Bell tests. In practice, however, the applicability of these states is hampered by noise effects such as photon losses. Real-world applications require therefore entanglement purification. The proposed setup is very attractive for detection of losses and can in particular be used to purify photon-number entangled states on site. If a photon-number correlated state, for example an EPR state, is used as input, the desired state passes the setup with a certificate, while states which suffered from photon losses are detected and can be rejected. The setup can be viewed as a filter which removes all undesired components of the quantum state but leaves the desired components unchanged.

Photon losses are an especially serious problem in quantum communication over long distances. It is not only a very common source of decoherence which is hard to avoid, but also typically hard to overcome. The on-site purification protocol described above can easily be adopted to a communication scenario such that it allows for the purification of a photon-number correlated state after transmission to two distant parties. A special advantage of our scheme lies in the fact that it does not only allow for detection of arbitrary photon losses, but is also applicable to many modes such that entanglement can be distributed and purified in a network.

Publications:

- "Quantum state engineering, purification, and number resolved photon detection with high finesse optical cavities", E. B. Nielsen, C. A. Muschik, G. Giedke, and K. G. H. Vollbrecht, Phys. Rev. A 81, 043832 (2010).

Reported progress towards Deliverable 2.5:
Quantum repeaters with entangled coherent states
(Partners CNRS/IO, CNRS/ENS)

During the second year, the CNRS/IO and CNRS/ENS teams, in collaboration with the group of applied physics-optics at the University of Geneva, has investigated the potential of such a remote preparation of entangled coherent states for quantum repeaters and long distance quantum communication. This study shows that entanglement of coherent states with arbitrary amplitudes can be created efficiently within tens of kilometer-long elementary links. However, it turns out from our calculations that, with realistic resources, large amplitude entangled coherent states $|\alpha|^2 >> 1$ cannot be distributed with high fidelity over longer distances using entanglement swapping operations. If one wants to distribute entangled coherent states with realistic resources and simple architectures, one therefore has to consider the limit of small amplitudes $|\alpha|^2 << 1$.

Publications:

N. Sangouard, C. Simon, N. Gisin, J. Laurat, R. Tualle-Brouri, and P. Grangier, *Quantum repeaters with entangled coherent states*, J. Opt. Soc. Am. B 27, A137 (2010).

Reported progress towards Deliverable 2.5:
Quantum repeater architecture in the CV regime
(Partner CNRS/ENS)

Quantum repeater architecture and scalability with CV is mostly unexplored. We propose in collaboration with other groups a first architecture based on entangled coherent states [1], which can be prepared remotely by subtracting non-locally a single photon from two quantum superpositions of coherent states. Such entanglement can further be distributed over longer distances by successive entanglement swapping operations using linear optics and photon-number resolving detectors. We evaluated the performance of this approach to quantum repeaters for long distance quantum communications. We show that, when using state-of-the-art photon counters and quantum memories, they achieve similar entanglement generation rates as repeaters based on single-photon entanglement. We also discuss potential developments which may take better advantage of the richness of entanglement based on continuous variables, including in particular efficient parity measurements. This first study should trigger further developments of this still unexplored field.

Publications

[1] *Atomic-ensemble-based quantum memory for sideband modulations* J. Ortalo, J. Cviklinski, P. Lombardi, J. Laurat, A. Bramati, M. Pinard, E. Giacobino, J. Phys. B 42, 114010 (2009)

Workpackage 3: Demonstration of mesoscopic CV quantum processors

Period covered: from 01/04/09 to 31/03/10
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 2 of the project

Significant progress has been also achieved by COMPAS members in the development and demonstration of methods for combating and suppressing losses or noise in CV quantum information processing. First, the experimental demonstration of the CV quantum erasure correcting code that had been proposed in the first year by partners ULB, DTU and FAU has been completed in the laboratory of partner DTU. This has led to an article which is accepted for publication in *Nature Photonics*. Partners FAU and DTU also made an important step towards filtering of CV quantum information with multiple photon counters. They experimentally implemented a scheme for discrimination of two pure coherent states that interpolates between the deterministic minimum-error discrimination and probabilistic error-free discrimination. Two devices were compared, one based on homodyne detection and the other based on photon counting. The superiority of the scheme based on photon counting was clearly demonstrated in the experiment.

Partners DTU, FAU and UP proposed and experimentally tested a scheme for continuous-variable environment-assisted quantum-information correction. This technique is applicable when some quantum information leaks into an environment that is accessible for measurement. A combination of environmental measurement and a feed-forward can strongly suppress a thermal noise added by the decoherence process. Partners DTU, FAU and UP also implemented a scheme for squeezed state quantum averaging where the resulting quadrature variance is a harmonic mean of the quadrature variances of input modes instead of the usual arithmetic mean. The procedure relies on interference of the two beams on a beam splitter followed by homodyne detection on one output beam and conditioning on measurement outcome being sufficiently close to zero. This protocol can be used to efficiently stabilize a set of squeezed light sources with statistically fluctuating noise levels.

Finally, partners DTU, FAU, and UP investigated in detail a protocol for the entanglement concentration from single copies of CV entangled states that have undergone an attenuation in a lossy channel with a varying transmission. The entanglement distillation is based on a weak local measurement on part of the corrupted state. The measurement outcome heralds success or failure of the protocol. Realistic models of transmission channel were considered, in particular a channel whose transmission profile is similar to profiles obtained experimentally in free-space transmission experiments, and a profile with two transmission peaks. It was shown that the distillation protocol is still successful for such realistic transmission channels, however, more uniform transmittance distributions tend to be more difficult for the distillation procedure. Furthermore, partner ULB analyzed the classical information capacity of Gaussian CV quantum channels, in particular channels exhibiting a memory effect (modeled with a Gauss-Markov process).

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 in Y1; No progress reported in Y2.

Partners: DTU, FAU, CNRS/IO

The first objective of this task is to investigate the generation and utilization of squeezed and entangled states of light for CV one-way quantum computing (or for teleportation-based implementation of quantum gates). 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.

Since these objectives are strongly connected with the engineering of non-Gaussian states of light, which is the subject of the ongoing Task 1.3 (in progress), the work of Deliverables 3.1 and 3.2 has been delayed to the third year. In between, much work has been carried out during the second year on a somewhat related task, namely the noiseless amplification of light. This is reported in Deliverable 1.5.

Task 3.2: Demonstrating CV quantum error correction

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

Status: Due month 24; Intermediate progress reported in Y1; Delivered.

Partners: DTU, FAU, ULB, and UP

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. The goal of this task is to develop quantum protocols for the detection or correction 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)

In the first year of the project, we have proposed and experimentally implemented a scheme for combating erasure errors in a CV quantum channel. This is the first CV quantum erasure-correcting code, which protects coherent states of light against complete erasure. This work has been completed and accepted for publication in *Nature Photonics* during the second year. For this reason, it is summarized here.

As shown in figure 1, the scheme encodes two coherent states into a bipartite 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.

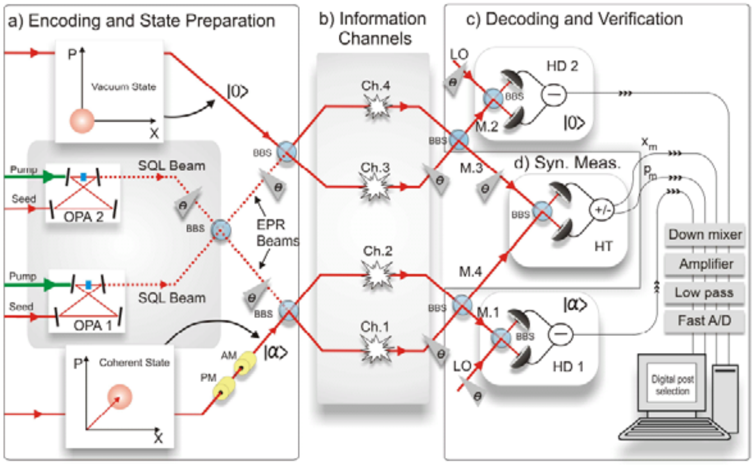


Fig. 1: *Schematic setup of the quantum erasure correcting code.*

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.

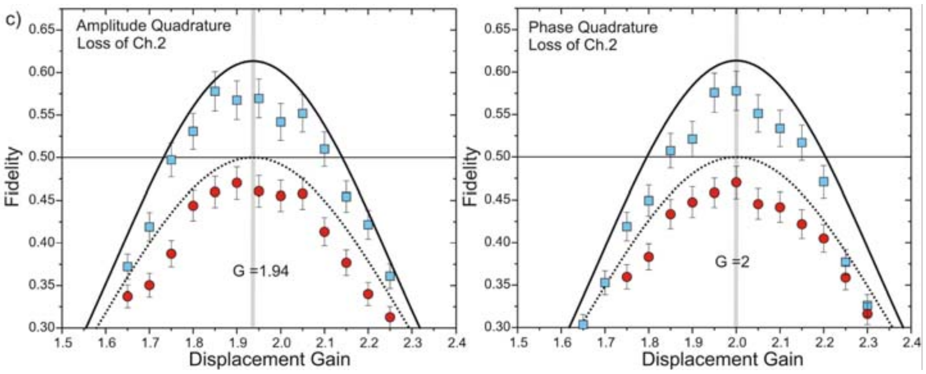


Fig. 2: *Protocol fidelity as a function of the displacement gain for deterministic quantum erasure correcting coding.*

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%.

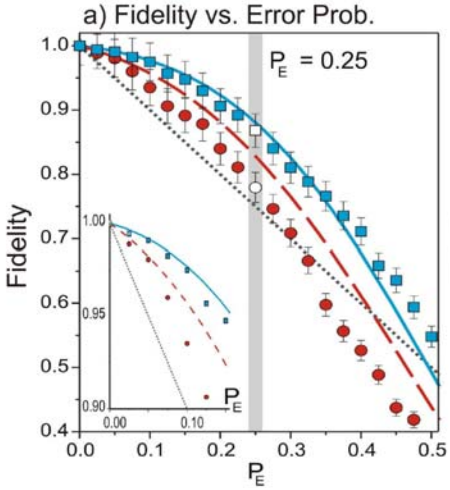


Fig. 3: *Protocol fidelity as a function of the error probability for probabilistic recovery of quantum information.*

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 ± 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:

M. Lassen, M. Sabuncu, A. Huck, J. Niset, G. Leuchs, N.J. Cerf and U.L. Andersen, *Experimental quantum erasure correction for continuous variables* , to appear in Nature Photonics (2010).

Presentations:

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].

<u>Task 3.3</u>: Demonstrating quantum noise filtering in CV systems

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. Finally, a probabilistic scheme for discrimination of optical coherent states is reported, which consists of an optimized displacement followed by postselection of a photon number resolving measurement.

Deliverable 3.4: *Filtering of noise in CV systems*

Status: Due month 24; Delivered at the end of year 1; Additional progress reported.

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

Reported progress towards Deliverable 3.4:

Displacement-controlled photon number resolving detector for coherent state discrimination
(Partner FAU, DTU)

An important step towards the filtering of continuous-variable quantum information with multi photon counters is the optimized discrimination of the corresponding quantum states with these measurement devices. Therefore, we demonstrate in this year's report a discrimination of two pure coherent states, before we move on to the more demanding task of filtering quantum information involving complex alphabets or mixed quantum states.

It is impossible to construct a measurement device for the perfect discrimination of two non-orthogonal quantum states. This basic postulate of quantum mechanics also holds for two *a priori* known coherent states (e.g. the signal $|-\alpha\rangle$ and $|+\alpha\rangle$). Therefore, the canonical task is to construct a measurement apparatus that maximizes the information gained, i.e. minimizes the errors in the measurement. This strategy is known as minimum error discrimination.

Several optimal and near optimal receivers have been proposed. Recently, two of them were experimentally demonstrated [1,2]. Another approach is the probabilistic strategy known as unambiguous state discrimination. This measurement produces either an error free or an inconclusive result. Both approaches are two limiting cases of a more general (intermediate) scheme allowing for erroneous and inconclusive results. It is plausible that there exists a trade-off between the rate of errors and inconclusive results, meaning that (starting from discrimination with minimum error) an increasing probability for inconclusive results can lower the error probability. In the discrimination of pure states, the minimal probability of errors for a fixed probability of inconclusive results is derived in [3].

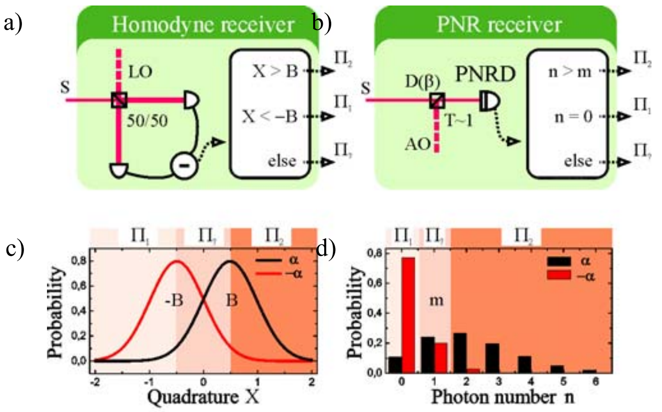


Fig.1. (a) Schematics of the homodyne receiver. The signal (S) is interfered with a local oscillator (LO). The photocurrents are subtracted resulting in a quadrature measurement. (b) Schematics of the photon number resolving (PNR) receiver. The signal (S) is interfered with an auxiliary oscillator (AO) and displaced by β. Finally, the signal is measured by a photon number resolving detector (PNRD) (c) Marginal distribution of the two signal states with intervals where the answers {−α, ?,+α} are guessed. (d) Photon number distribution of two signal states. In the examples (c,d), we assume a signal with $|\alpha|^2 = 0.24$ and a displacement of $\beta = 1$.

We demonstrate a photon number resolving (PNR) receiver in the intermediate regime and compare it to the standard homodyne (HD) receiver (Fig. 1(a)). The new receiver consists of an optimized displacement operation and a photon number resolving detector (Fig. 1(b)). The scheme is similar to the one in [2], however the photon number resolving detector replaces a simple threshold detector (on/off detector). The two schemes generate different distributions of measurement outcomes as shown in the Figures 1(c) and (d). The states are separated in quadrature and photon number space, respectively.

The states are then discriminated in a single-shot measurement by guessing $|-\alpha\rangle$, $|+\alpha\rangle$ or ? (corresponding to an inconclusive result) associated with the measurement outcomes Π_1, Π_2, $\Pi_?$, shown as colored intervals in the figures. For the new PNR receiver, we assume inconclusive results to occur when a small but non-zero photon number is detected. Conclusive results are described by no photons measured and by a measured photon number larger than the postselection parameter m. For the HD receiver, we assume inconclusive results to occur when a small quadrature value $|X| < B$ is measured. Conclusive results are described by large positive and negative quadrature values.

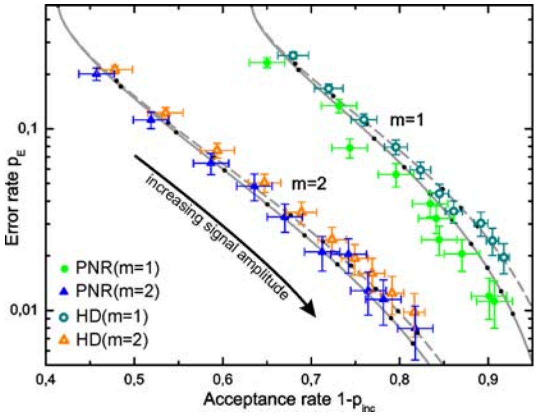


Fig. 2. *Experimental error rates versus acceptance rates with increasing signal amplitudes for the PNR receiver and the homodyne receiver. For this comparison the success rate of both schemes is fixed to the one, that is theoretically reached by the PNR receiver. The theoretical predictions for the homodyne receiver (grey dashed line) and the PNR receiver (solid line) are shown. Experimental data is also presented. Data was corrected for the receivers quantum efficiencies.*

We find that our PNR receiver can discriminate the signal involving inconclusive results in the intermediate region of USD and minimum error state discrimination. As shown in Fig. 2, the new receiver (solid lines) can discriminate the signal with smaller error rate than the homodyne receiver (dashed lines) in theory. A detailed theoretical description can be found in [4]. Furthermore, we demonstrate that the receiver surpasses the homodyne receiver in the experiment (see Fig.2 and [5] for details). This is especially relevant since the homodyne receiver can be proven optimal for all Gaussian measurements including conditional feed forward for the deterministic [6] as well as the non-deterministic strategy [5].

References:

[1] R. L. Cook, et al., "Optical coherent state discrimination using a closed-loop quantum measurement.", Nature 446, 774 (2007).
[2] C. Wittmann, et al., "Demonstration of Near-Optimal Discrimination of Optical Coherent States", Phys. Rev. Lett. 101, 210501 (2008).
[3] A. Chefles et al., "Strategies for discriminating between non-orthogonal quantum states", J. Mod. Opt. 45, 1295 (1998).
[4] C. Wittmann, et al., "Discrimination of Optical Coherent States using a Photon Number Resolving Detector", J. Mod. Opt Journal Of Modern Optics 57, 213 - 217 (2010).
[5] C. Wittmann, et al., "Demonstration of Coherent-State Discrimination Using a Displacement-Controlled Photon-Number-Resolving Detector", Physical Review Letters 104, 100505 (2010); C. Wittmann, U. L. Andersen, M. Takeoka, D. Sych, and G. Leuchs, arXiv:1002.0232 [quant-ph], To be published in Phys. Rev. A (2010).
[6] M. Takeoka et al., "Discrimination of the binary coherent signal: Gaussian-operation limit and simple non-Gaussian near-optimal receivers", Phys. Rev. A 78, 022320 (2008).

Publications:

C. Wittmann, U. Andersen, and G. Leuchs, "*Discrimination of optical coherent states using a photon number resolving detector*", Journal of Modern Optics 57, 213 - 217 (2010).
C. Wittmann, U. L. Andersen, M. Takeoka, D. Sych, and G. Leuchs, "*Demonstration of Coherent-State Discrimination Using a Displacement-Controlled Photon-Number-Resolving Detector*", Physical Review Letters 104, 100505 (2010).
C. Wittmann, U. L. Andersen, M. Takeoka, D. Sych, and G. Leuchs, "*Demonstration of Coherent-State Discrimination Using a Displacement-Controlled Photon-Number-Resolving Detector*", arXiv:1002.0232 [quant-ph], To be published in Phys. Rev. A (2010).

Conference Presentations:

C. Wittmann, U.L. Andersen, M. Takeoka, K.N. Cassemiro, M. Sasaki, G. Leuchs, "Near-Optimal Discrimination of Optical Coherent States involving inconclusive results", 11th international conference on squeezed states and uncertainty relations, June 22 – 26, 2009, Olomouc, Czeck Republic
C. Wittmann, U. L. Andersen, M. Takeoka, D. Sych, and G. Leuchs, "Displacement Controlled Photon Number Resolving Detector for Optical Coherent States." DPG Spring Meeting, March 8-12, 2010, Hannover, Germany
C. Wittmann, U. L. Andersen, M. Takeoka, D. Sych, and G. Leuchs, "Displacement Controlled Photon Number Resolving Detector for Coherent State Discrimination" CLEO/QELS, May 16-21, 2010, San Jose, USA

Reported progress towards Deliverable 3.4:
Environment-assisted quantum-information correction for continuous variables
(Partner DTU, FAU, UP)

Quantum-information protocols are inevitably affected by decoherence which is associated with the leakage of quantum information into an environment. In this work we have addressed the possibility of recovering the lost quantum information by performing a measurement of the environment. More specifically, we have proposed a simple environmental measurement strategy that under certain circumstances fully restores the lost quantum information of the signal state although the state is not reconstructed with unit fidelity. We have implemented the protocol for which information is encoded into conjugate quadratures of coherent states of light and the noise added under the decoherence process is of Gaussian nature. The correction protocol has been tested using both a deterministic as well as a probabilistic strategy.

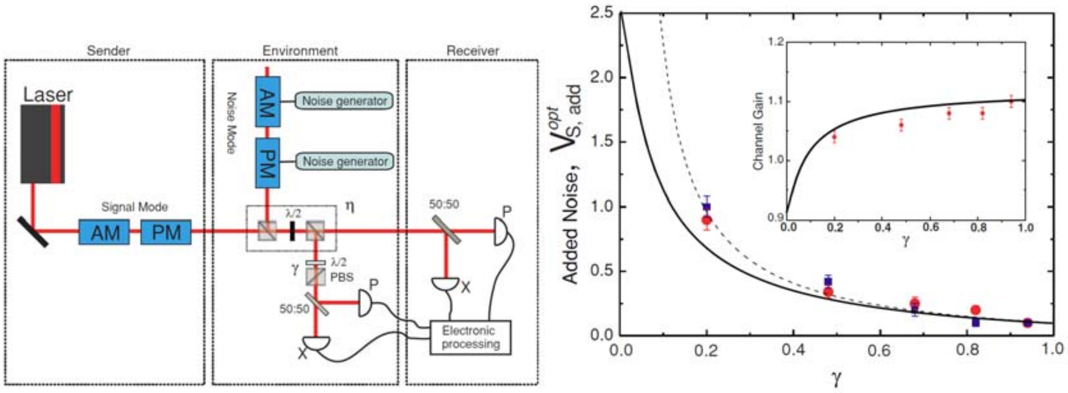


Figure 1

The experimental setup is shown in Fig. 1 (left). Quadrature information is encoded onto a coherent state of light is which is sent through an environment. The environment is simulated by mixing the signal state with a thermal state in a beam splitter with variable reflectivity. The channel output is sent to the receiving station where a heterodyne measurement is performed. Part of the state has leaked into the environment which is then measured using an environmental heterodyne detector with efficiency γ. The measurement results are shown in figure Fig 1 (right). Without any use of the environmental measurement, the signal has been affected by 2.5dB of excess noise. However, by correcting the information based on the environmental measurements, the added noise can be almost completely removed.

Publications:

Environment-assisted quantum-information correction for continuous variables
Metin Sabuncu, Radim Filip, Gerd Leuchs, and Ulrik L. Andersen, Physical Review A 81, 012325 (2010)

Conference presentations:

Environmental Assisted Channel Noise Erasure for Quantum Communication, M. Sabuncu, R. Filip, G. Leuchs, and U. L. Andersen, Poster presentation, QCMC, University of Calgary, Canada, 19-24 August (2008).

Measurement induced decoupling of Gaussian Noise for quantum communication, Metin Sabuncu, Radim Filip, Gerd Leuchs and Ulrik L. Andersen, Poster presentation, QIPC, Barcelona (2007).

Reported progress towards Deliverable 3.4:
Experimental Demonstration of Squeezed State Quantum Averaging
(Partner DTU, FAU, UP)

We have proposed and experimentally demonstrated a universal quantum averaging process implementing the harmonic mean of quadrature variances. The averaged variances are prepared probabilistically by means of linear optical interference and measurement induced conditioning. We verified that the implemented harmonic mean yields a lower value than the corresponding value obtained for the standard arithmetic mean strategy. The effect of quantum averaging has been experimentally tested for squeezed and thermal states as well as for uncorrelated and partially correlated noise sources. The harmonic mean protocol can be used to efficiently stabilize a set of squeezed light sources with statistically fluctuating noise levels.

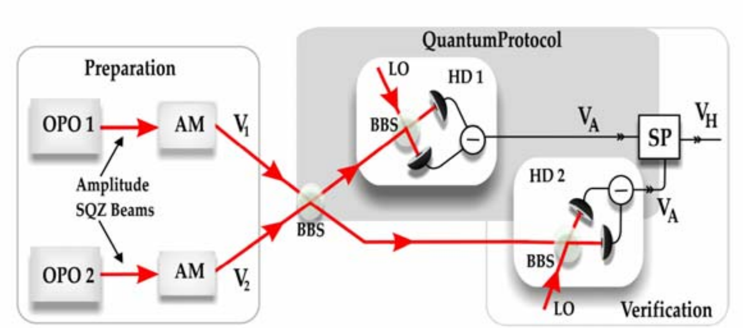


Figure 1

The protocol for the averaging of two states is shown in Fig.1. Two arbitrary Gaussian states are prepared using two squeezers and two noisy modulators. The averaging procedure is executed by mixing the two copies on a 50/50 beam splitter and herald one output conditioned on the homodyne measurement of the other output. The state is heralded if the measurement outcome lies within a predefined interval. Some of the measurement results are shown in Figure 2 where we plot the averaged variance as a function of the success rate (which depends on the length of the selection interval). On the left figure, two squeezed states served as the input whereas in the right figure we used a squeezed state and a thermal state. The standard (arithmetic) averaging of the two states follows the blue dashed line. By using the new approach, harmonic averaging is possible as shown by the experimental data points (and black curves).

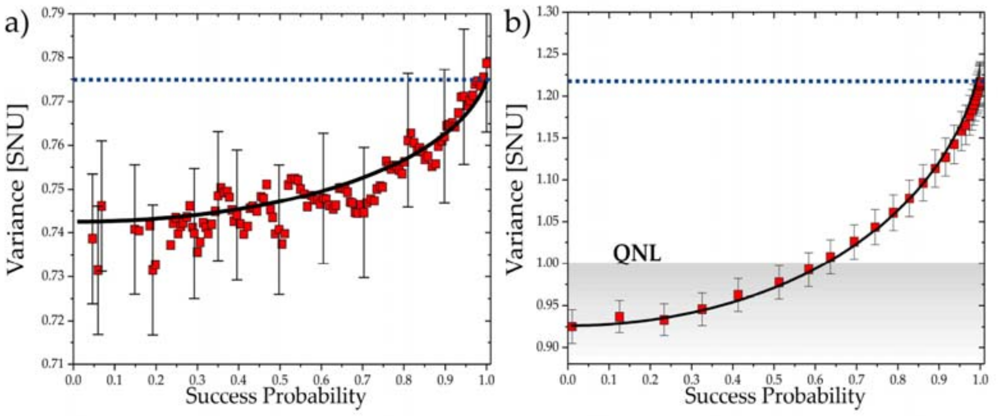


Figure 2

Publications:

Experimental Demonstration of Squeezed State Quantum Averaging
Mikael Lassen, Lars Skovgaard Madsen, Metin Sabuncu, Radim Filip, and Ulrik L. Andersen, Submitted to Physical Review A

Conference presentations:

Squeezed State Averaging
Mikael Lassen, Lars Skovgaard Madsen, Metin Sabuncu, Radim Filip, and Ulrik L. Andersen, Poster, Physics of quantum electronic, January 3-7, Snowbird, Utah, USA (2010)

Experimental Demonstration of Squeezed State Quantum Averaging
Mikael Lassen, Lars Skovgaard Madsen, Metin Sabuncu, Radim Filip, and Ulrik L. Andersen, Talk at CLEO/IQEC, San Jose, USA, May (2010)

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 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.

Additional progress towards Deliverable 3.5:

Exprimental continuous-variable entanglement distillation of non-Gaussian states
(Partners DTU, FAU and UP)

In the first year of the COMPAS project, we 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. Since the transmission coefficient of a channel is fluctuating, the resulting transmitted state is a non-Gaussian mixed state. We have shown it is possible to distill non-Gaussian states based on a weak measurement of the corrupted states and heralding of the remaining state. In the previous work, two specific transmission channels, a discrete erasure channel and a simulated short-term free-space transmission channel with the distributed peak close to the 100% transmittance level, were investigated with successful distillation results achieved [1]. In this report, we further demonstrate the effectiveness of our distillation protocol on more practical scenarios for a transmission channel. We consider a transmission channel in which the highest transmittance level may not have the biggest weight in the probability distribution. This distribution is similar to some of our recently obtained transmission profiles in a free space experiment where coherent states were sent over about 200m. Besides, there might be more than one peak in the probability distribution diagram. For instance, some strong beam pointing noise due to bad atmospheric condition, such as in weather with snow fall, will induce another distributed peak in the area of low transmittance levels.

In the following we show the performance of the distillation protocol for two different transmittance distributions. First, the mixed state has a peak of the transmittance distribution around 0.8 (Fig. 1-1). Second, we incorporate a second peak which is located around the transmittance level of 0.3 (Fig. 2-1).

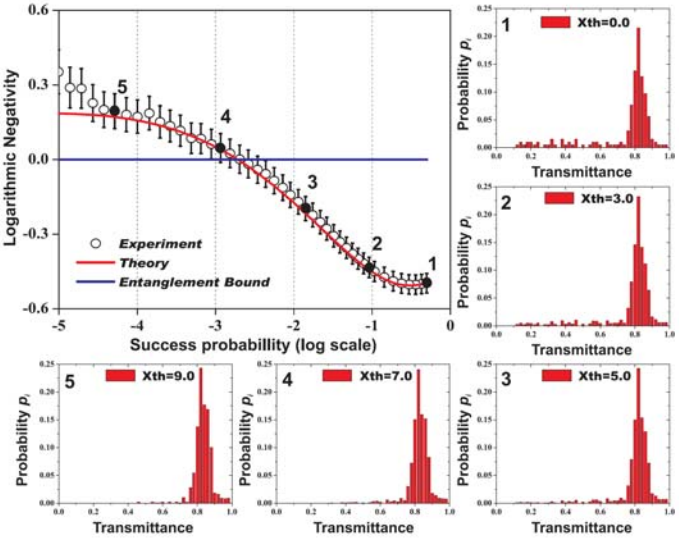


Fig. 1 *Experimental and theoretical results outlining the distillation of an entangled state from a simulated continuous lossy channel in which the peak of the transmittance distribution is lying on 0.8. The experimental results are marked by circles and the theoretical prediction by the red solid curve. The evolution of the weights of the various constituents in the mixed state as the threshold value is changed is shown in the figures labeled 1-5. The error bars of the log-negativity represent the standard deviations.*

As shown in Fig. 1, after propagation through the one-peak displaced channel the Gaussian LN of the mixed state is found to be -0.50 ±0.04. The state is subsequently distilled and the change in the Gaussian LN as the threshold value increases (and the success probability decreases) was investigated both experimentally (black open circles) and theoretically (red curve). The evolution of the mixture is directly visualized in the series of probability distributions in Fig. 1-1 to 1-5 corresponding to the postselection thresholds X_{th} =0.0, 3.0, 5.0, 7.0, 9.0 respectively. We see that the distribution weights of the low transmittance levels is gradually reduced, while the weights of the high transmittance levels is increased as the postselection process becomes more and more restrictive by increasing the threshold value. E.g. for X_{th} = 9 the probabilities associated with transmission levels lower than 0.7 are decreased from 20% before distillation to 1.4% and the probability for transmission levels higher than 0.7 transmission are increased to 98.6% as opposed to 80% before distillation. It is thus clear from these figures that the highly entangled states in the mixture have larger weight after distillation, and the corresponding Gaussian LN after distillation rises to 0.19±0.06 with the success probability of 5.16×10^{-5}.

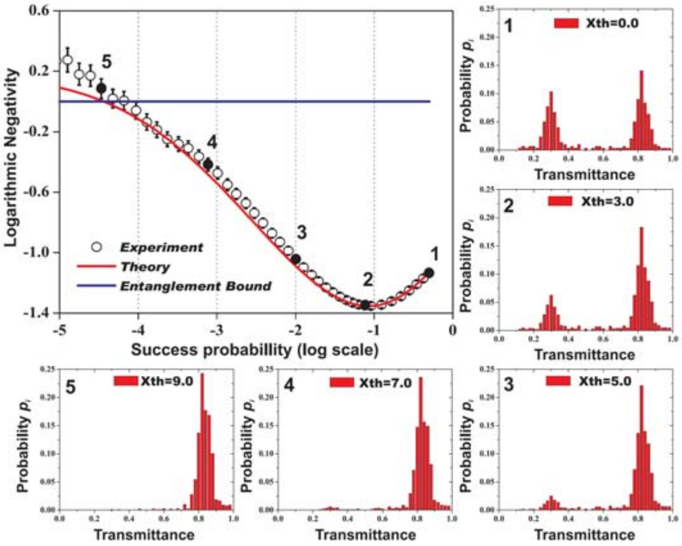


Fig. 2 *Experimental and theoretical results outlining the distillation of an entangled state from a simulated continuous lossy channel in which the transmittance levels are distributed as such that there are two peaks at both high transmittance levels (0.8) and low transmittance levels (0.3). The experimental results are marked by circles and the theoretical prediction by the red solid curve. The evolution of the weights of the various constituents in the mixed state as the threshold value is changed is shown in the figures labeled 1-5. The error bars of the log-negativity represent standard deviations.*

We now turn to investigate the distillation after propagation through the two-peak displaced channel as shown in Fig. 2-1. Before distillation the Gaussian LN of the mixed state is found to be -1.13 ±0.02. Likewise, the relation between the distilled Gaussian LN and the success probability was investigated both experimentally and theoretically. The results are shown in Fig. 2 by black open circles and the red curve, respectively. Through the probability distribution plots in Fig. 2-1 to 11-5, the evolution of the mixture corresponding to different choices of postselection thresholds was illustrated with the same trend that we see on the distillation of the one-peak displaced channel. For $X_{th} = 9$ the probabilities associated with transmission levels lower than 0.7 are decreased from 48% before distillation to 1.6% and the probability for transmission levels higher than 0.7 transmission are increased to 98.4% as opposed to 52% before distillation, and the corresponding Gaussian LN after distillation reaches 0.19±0.06 with the success probability of 3.39×10^{-5}.

In summary, we have shown that the distillation of Gaussian entanglement is still successful for some more general transmission channels. On the other hand, we should note that the successful entanglement distillation depends on the transmittance distribution of the lossy channel: more uniform transmittance distributions turned out to be more difficult for the distillation procedure. 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:

[1] R.F. Dong, M. Lassen, J. Heersink, C. Marquardt, R. Filip, G. Leuchs, and U. L. Andersen, "Continuous Variable Entanglement Distillation of Non-Gaussian States", Phys. Rev. A (accepted).

Additional progress towards Deliverable 3.5:
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. 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 CV quantum 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. This problem is very important in optical communication based on the quadrature components of light, which are especially powerful because of their associated detection scheme, namely homodyne detection. This advantage of CV quantum communication is well illustrated with CV quantum key distribution, which now appears as a credible alternative to single-photon based quantum key distribution.

Partner ULB showed that, if the standard conjecture that Gaussian input states minimize the output entropy of Gaussian channels is taken for granted, the optimal modulation above some energy threshold 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 below the threshold was also investigated, along with some issues on the ultimate information capacity while optimizing over the environment.

Publications:

J. Schäfer, D. Daems, E. Karpov, and N.J. Cerf, *Capacity of a bosonic memory channel with Gauss-Markov noise*, Phys. Rev. A 80 (2009) 062313.

Conference presentation:

E. Karpov, J. Schäfer, and N. J. Cerf, *Capacity of bosonic additive noise channels*, SPIE Photonics Europe, Brussels (Belgium), 12-16 April 2010. [CONTRIBUTED TALK]

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 from experimental data	1	7	R	PU	12	Yes	12	Additional work reported
D1.2	Exploration of CV quantum computing with non-Gaussian quantum states	1	7	R	PU	24	Yes	24	
D1.3	Generation of high photon number Fock states	1	7	R	PU	24	No	36	Work in progress
D1.4	Generation of monomode and multimode cat states	1	7	R	PU	24	No	36	Work in progress
D1.5	Measurement-induced nonlinear operations	1	7	R	PU	36	Yes	24	Delivered in advance
D1.6	Detector process tomography	1	7	R	PU	24	Yes	24	
D2.1	Engineering and manipulating states in atomic quantum memory	2	8	R	PU	36	No	36	Work in progress

D2.2	Light-atoms quantum interface for quantum information processing	2	8	R	PU	24	Yes	24	Additional progress expected
D2.3	Interfacing light with atoms in optical lattices and trapped ions	2	8	R	PU	24	Yes	24	
D2.4	Alternative methods for generating non-Gaussian states using Kerr nonlinearity	2	8	R	PU	24	Yes	24	
D2.5	CV quantum repeaters based on complex quantum network geometries	2	8	R	PU	24	Yes	24	
D3.1	Cat-states implementation of the sign-flip operation	3	9	R	PU	36	No	36	
D3.2	Assessment of the implementation of the C-NOT and Hadamard gates	3	9	R	PU	36	No	36	Intermediate progress reported
D3.3	Demonstration of CV quantum error correction	3	9	R	PU	24	Yes	24	
D3.4	Filtering of noise in CV systems	3	9	R	PU	24	Yes	12	Delivered in advance (additional work reported)
D3.5	Distillation or concentration of CV entanglement	3	9	R	PU	36	Yes	12	Delivered in advance (additional work reported)

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	12	
MS2	Generation of CV cluster states of light	1	7	24	No		This is conditioned on a better engineering of non-Gaussian states of light, which is the subject of Task 1.3 (currently in progress).
MS3	Generation and breeding of Schrödinger cat states of light	1	7	24	No		This is conditioned on a better engineering of non-Gaussian states of light, which is the subject of Task 1.3 (currently in progress).
MS4	Efficient quantum memory for light based on cold atoms	2	8	24	Yes	24	
MS5	Experimental entanglement distillation/purification	3	9	24	Yes	24	
MS6	Demonstration of atomic Schrödinger cat states	2	8	24	No		Due to the huge number of atoms in the dipole trap necessary to achieve a strong light-atom coupling an extreme degree of control of the technical parameters is required. This required unforeseen additional efforts in constructing a low-phase noise microwave source delayed the production of atomic Fock-states due to the requirement of ultra-low-noise two-photon radio-frequency-pulses.
MS7	Experimental small-scale few-modes CV quantum processor	3	9	36	No	36	

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. There was no specific deliverable in WP4 during the second year of the project, except for the current activity report.

Project website (Task 4.1)

The project website http://optics.upol.cz/compas/ had been working since month 6 of the project, and is regularly managed and updated. It contains 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 is the first action towards knowledge dissemination.

Conference and meeting organization (Task 4.2)

Among the other actions towards knowledge dissemination, it was planned to organize workshops 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)

CV-QIP'08 was not organized since a related conference was organized: *1st Solvay workshop on Bits, Quanta, and Complex Systems: Modern approaches to photonic information processing*, Palace of the Academies in Brussels, April 30 – May 3, 2008. This was organized under the auspices of the International Solvay Institutes (Brussels). Continuous-variable quantum information was one of the themes discussed during this workshop, and a good fraction of the COMPAS members attended it.

CV-QIP'09 was not organized since 2 related conferences were organized: *11th International Conference on Squeezed States and Uncertainty Relations (ICSSUR'09)* and *4th Feynman Festival*, Olomouc, Czech Republic, June 22 – 26, 2009. A section of these conferences was devoted to continuous variables quantum information, and was placed under the banner of COMPAS (which contributed to a small fraction of the budget). Again, many COMPAS members attended and gave talks during these conferences, in particular in Section B of ICSSUR'09.

CV-QIP'10 : this *7th Continuous-Variable Quantum Information Processing workshop* will be held in Ammersee (near Munich), Germany, June 11-14, 2010. It is organized by partner MPG, and will also be the occasion for holding the second year Project Coordination Meeting. It will immediately be followed by the second year Project Review Meeting.

Project coordination meetings

The 1st year Project Coordination Meeting of COMPAS was held on an informal basis during the *11th International Conference on Squeezed States and Uncertainty Relations (ICSSUR'09)*, Olomouc, Czech Republic, June 22 – 26, 2009.

The 2nd year Project Coordination Meeting of COMPAS will be held on an informal basis during the *7th Continuous-Variable Quantum Information Processing workshop* in Ammersee (near Munich), Germany, June 11-14, 2010.

Planned activities in year 3

The following workshop, namely CV-QIP'11, will be organized within COMPAS by partner POTSDAM. It is tentatively planned for the Spring 2011 and should take place in Berlin. The 3rd year Project Coordination Meeting of COMPAS will hopefully be held during this workshop, as well as the final Project Review Meeting.

Contribution to activities at the level of FET-Open (Task 4.3)

These activities were reported in Section 2 of this report, so we do not repeat them 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.

Reflection on the outlook of research in continuous-variable QIPC (Task 4.4)

The coordinator (ULB) and deputy coordinator (UP), helped by all members of the consortium, have been working on a short roadmap (reflection paper) 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, potential "medium-term scientific spin-offs"). This roadmap can be found in the Appendix of the present activity report (cf. Section 7).

This continuous-variable QIPC roadmap is based on brainstorming sessions that were organized during previous CV-QIP workshops, and mainly on the outcome of a specific meeting that was organized during the second year of the project:

COMPAS roadmap meeting, Hôtel Le Dôme, Brussels, November 30th – December 1st, 2009.

One or several members of all COMPAS teams attended this workshop.

Finally, let us mention that the "networking", which is another goal of the management workpackage, was well achieved during the second year of the project. There were numerous bilateral collaboration visits among the project partners, as reflected by the large number of joint works.

6. Explanation of the use of the resources

The tables with the explanation of the major cost items for each partner will be provided at a later time as we could not access the NEF platform on time.

7. Appendix: Roadmap on continuous-variable QIPC

The current version of the roadmap on continuous-variable QIPC is attached to this periodic activity report. Note that it should be viewed as a “living document”, which will be updated following the progress of the field. Although it is aimed at providing a broad overview of the CV-QIPC research, it is not meant to be fully exhaustive.