# 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 2010 to 31st March 2011

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

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

# Declaration by the scientific representative of the project coordinator

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

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate):

  ■ has fully achieved its objectives and technical goals for the period;

  ☐ has achieved most of its objectives and technical goals for the period with relatively minor deviations;

  ☐ has failed to achieve critical objectives and/or is not at all on schedule.

- The public website is up to date, if applicable.
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 6) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 5 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

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

Date: ........6..../ .June....../ .2011.........

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<br>CNRS/ENS | FR | Philippe Grangier (WP1 leader)<br>Elisabeth Giacobino | EXP<br>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).

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/

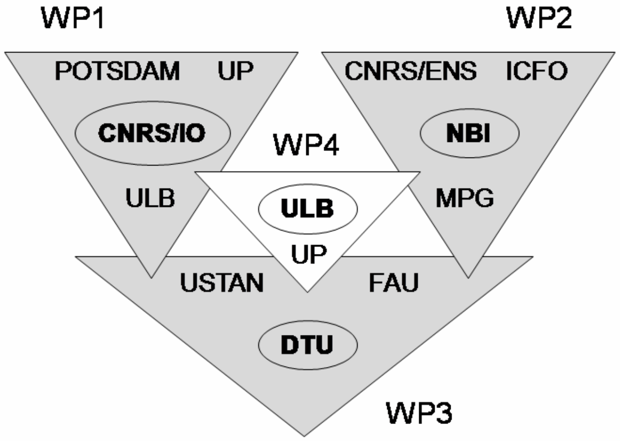
It is anticipated that the COMPAS project will have a strong impact on the future of ICT-related technologies and further strengthen the pan-European cooperation in a research area where Europe has started to establish itself at the leading edge.

## 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 01/04/10 to 31/03/11
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 3 of the project

One of the main objectives of WP1 is to develop tools and techniques that are subsequently explored in WP3 to demonstrate various CV quantum information processing schemes, in particular quantum gates for qubits encoded as superpositions of coherent states (cat-like states). Partner DTU therefore developed a new experimental setup for the generation of cat-like states by subtraction of a single photon from squeezed vacuum state. A specific feature of this cat-state source is that a picosecond pulsed laser is used for pumping a nonlinear crystal. On one hand, this ensures that the generated states are well localized in time. On the other hand, this largely circumvents problems arising from group velocity dispersion that may be significant when femtosecond pulses are employed. Partner CNRS/IO mastered the experimental technique of conditional single-photon addition based on stimulated parametric down-conversion followed by detection of idler photon. The procedure was tested on coherent states at it was verified that the generated states are highly non-Gaussian and posses a negative Wigner function. The photon addition can be combined with photon subtraction to implement a high-fidelity noiseless quantum amplifier. This has been successfully experimentally tested by partner UP in collaboration with Prof. Marco Bellini. The resulting amplifier probabilistically increases the amplitude of coherent states without adding noise and it fully preserves coherence. This amplifier can thus be used to increase the size of cat-like states formed by a superposition of two coherent states, and it thus greatly facilitate quantum computing with cat states where a sufficient size of the cat is critical.

In current experiments, the cat-like states as well as other highly non-classical non-Gaussian states of light are almost exclusively produced from squeezed states. It is therefore essential to engineer and optimize the sources of squeezed states. Partner FAU succeeded in generation of multimode CV hyper-entangled state formed by squeezing a cylindrically polarized mode of light. Furthermore the generation of squeezing in a whispering gallery resonator was achieved. This optical parametric oscillator (OPO) requires extremely weak pumping power to reach the threshold, which may in the future enable pumping the OPO with non-classical light. Finally, a macroscopic CV analog of the singlet two-photon Bell state was experimentally demonstrated by partner FAU.

Another goal of WP1 is to explore various models of CV quantum computing. Partner USTAN generalized the model of ancilla-driven quantum computation to continuous quantum variables. In this quantum computing model, operations on the quantum register are performed remotely by manipulating and measuring a fully controlled ancilla that couples to the register via a fixed unitary interaction. The advantage of this approach is a prospect for better scalability. Partners USTAN and FAU also suggested topological quantum computation model using CV abelian anyons created on the surface of CV analogues of Kitaev’s lattice model. In this model, universal quantum computing can be realized from topologically protected CV resources. The above computing models share some similarities with the measurement-based quantum computing. In previous years of the project, partner POTSDAM had demonstrated inherent limitations of one-way quantum computing with Gaussian multimode squeezed cluster states. These results have now been complemented with identification of a general class of CV quantum states that can be used to perform efficient measurement-based quantum computing. It turns out that non-Gaussian states emerge as a crucial resource even in this scenario. Finally, the specific role of non-Gaussian states in another generic informational task, namely quantum bit commitment, has been exhibited. Partner ULB proposed a non-Gaussian optical scheme for quantum bit commitment, whose asymptotic security against Gaussian cheating was demonstrated.

## **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

Additional results related to the characterization of CV states and generation of CV entanglement have been obtained during the third reporting period, which are reported as additional results towards Deliverable 1.1. In particular, we report on work by partners ULB and UP related to the properties of non-Gaussian mixed quantum states. Then, we report on several additional experimental results on the resources (squeezing and entanglement sources) by partner FAU: (1) Theoretical and experimental demonstration of entanglement between different degrees of freedom by quadrature squeezing cylindrically polarized modes. (2) Squeezed states are generated inside a lithium niobate whispering gallery mode resonator. The high quality factor of the WGMR enables two-mode squeezing at extremely low pump thresholds and direct observation of squeezing of the individual output beams far above threshold. (3) A macroscopic analog of the singlet two-photon Bell state is experimentally realized.

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### **Additional progress related to Deliverable 1.1:**

*Extended (non-Gaussianity bounded) uncertainty relations for mixed states*
(Partner ULB)

A central problem in CV quantum information is to better understand the non-Gaussian states and the non-Gaussian 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 error correction, CV quantum computing, and for tests of nonlocality based on homodyne detection. 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".

During the first year of the project, partner ULB had investigated how Hudson's theorem can be extended to mixed states, among which not only Gaussian states (and even non-Gaussian mixtures of 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. 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) {1}.

During the second and third year of the project, we have pursued this work, which led us to the even more fundamental problem of generalized 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. Our result is thus a non-Gaussianity bounded uncertainty relation, which is tighter than the usual uncertainty relation. 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. Incidentally, we have proven that among the states having a fixed non-Gaussianity, those which have the minimum uncertainty (minimize the product of quadrature variances) happen to be simply the Fock states. This extends to all number states the well-known property that the vacuum state saturates the uncertainty relation.

**References:**

{1} A. Mandilara, E. Karpov, and N. J. Cerf, *Extending Hudson's theorem to mixed quantum states*, Phys. Rev. A 79 (2009) 062302.

**Publications:**

A. Mandilara, E. Karpov, and N. J. Cerf, *Gaussianity bounds for quantum mixed states with a positive Wigner function*, J. Phys.: Conf. Ser. 254, 012011 (2010).

A.Mandilara, E. Karpov and N. J. Cerf, *Uncertainty, Entropy and non-Gaussianity for mixed states*, Proc. SPIE 7727, 77270H (2010).

A.Mandilara, E. Karpov and N. J. Cerf, *Non-Gaussianity bounded uncertainty relation for mixed states*, to be submitted to Phys. Rev. A.

**Conference presentations:**

*Uncertainty, Entropy and non-Gaussianity for mixed states*, A. Mandilara, E. Karpov, and N.J. Cerf, SPIE Photonics Europe, April 13, 2010, Brussels, Belgium. [CONTRIBUTED TALK]

*Extended uncertainty relations for mixed states*, A. Mandilara, E. Karpov, and N.J. Cerf, 7th Workshop on Continuous-Variable Quantum Information Processing (CV-QIP'10), Herrsching (Ammersee), Germany, 11-14 June, 2010. [POSTER]

*Non-Gaussianity bounded uncertainty relation*, A. Mandilara, E. Karpov, and N.J. Cerf, 12th International Conference on Squeezed states and Uncertainty relations and 5th Feynman Festival, 2-5 May 2011, Foz do Iguacu, Brazil. [INVITED TALK]

*Non-Gaussianity bounded uncertainty relation*, A. Mandilara, seminar on 25/02/2011 at Condensed Matter Section, ICTP Institute, Trieste, Italy.

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**Additional progress related to Deliverable 1.1:**
*Detecting quantum states with positive Wigner function beyond mixtures of Gaussian states*
(Partner UP)

Nonclassical states of a quantum harmonic oscillator are an indispensable resource for quantum technology. The basic nonclassical states, squeezed states are Gaussian, i.e., their Wigner function is Gaussian, and they can be prepared by a unitary operation generated by a quadratic bosonic Hamiltonian. Squeezed states are a resource for the preparation of any Gaussian state and implementation of any Gaussian operation. However, a more fundamental resource exists in the form of single-photon state. If it is ideal it allows for the construction of any quantum state and more diverse quantum operations. However, a single-photon state has a non-Gaussian Wigner function, reaching negative values as a consequence of higher-order quantum nonlinearity in the state preparation. It is still a challenge for many sources to verify that the produced quantum states possess at least some of the nontrivial properties of the desired single-photon state that go beyond the framework of experimentally well managed mixtures of Gaussian states.

We propose a criterion giving a sufficient condition for quantum states of a harmonic oscillator not to be expressible as a convex mixture of Gaussian states [1]. This nontrivial property is inherent to, e.g., a single-photon state and the criterion thus allows one to reveal a signature of the state even in quantum states with a positive Wigner function. The criterion relies on directly measurable photon number probabilities and enables detection of this manifestation of a single-photon state in quantum states produced by single-photon sources in a weak coupling regime. Further we have applied this criterion and compare it with the witness based on negativity of Wigner function for sources based on a subtraction of photon from the squeezed state [2] and the anti-correlation parameter (intensity-correlation measurement) for the atomic and solid state sources [3].

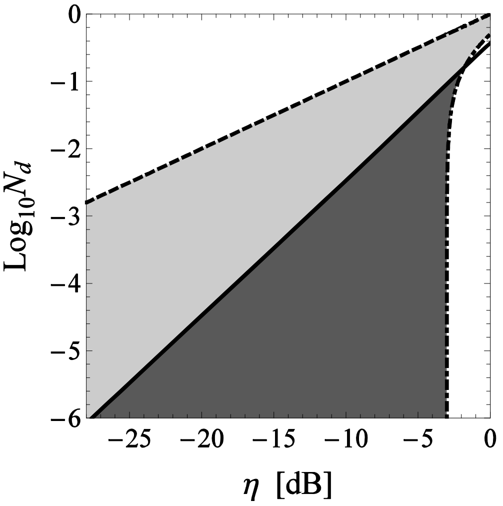

**Fig.1** *Comparison between criterion based on negativity of the Wigner function (white area below dash-dotted curve) and the proposed criterion (area below solid curve) for the single photon generated by the source in a weak coupling regime. $\eta$ stands for overall efficiency and Nd is overall mean photon number of the background noise. For states lying below the dash-dotted curve the Wigner function is negative. The dark gray area stands for the states with a positive Wigner function that are not a mixture of Gaussian states. For comparison, the threshold for the background noise degrading the states to mixtures of coherent states is depicted by a dashed curve. The states above this curve can be prepared as a mixture of coherent states.*

## Publications:

[1] Radim Filip and Ladislav Mišta, Jr., Phys. Rev. Lett. **106**, 200401 (2011)
[2] Ladislav Mišta, Jr. and Radim Filip, in preparation.
[3] Radim Filip, Frederic Grosshans and Lukáš Lachman, in preparation.

## Additional progress related to Deliverable 1.1:

*Entangling different degrees of freedom by quadrature squeezing cylindrically polarized modes* (Partner FAU)

Entanglement plays a major role in quantum information science [1] and finds applications in quantum teleportation, quantum computation and quantum cryptography. As a resource the creation and control of continuous variable entangled states is of great importance. In continuous variables, various methods have been developed to generate, inter alia, quadrature, polarization and spatial entanglement [2]. In particular multimode systems have become ideal candidates to successfully build complex quantum information systems [3], especially if multiple modes within a single laser beam are exploited [4]. Furthermore, continuous variable orbital angular momentum states are expected to have great potential for improving quantum information protocols [5]. In the discrete variable regime, hyper- and hybrid-entangled states have gained increased interest [6] and recently a theoretical proposal for continuous variable hyper-entangled states was made [7].

We present theoretical and experimental results of non-classical states of light generated in modes which have a complex spatial as well as a complex polarization structure, namely radially and azimuthally polarized modes. We show that squeezing one of these modes results in a highly complex continuous variable entanglement state. We introduce these novel entangled states, which have a very intriguing structure since they contain entanglement between different degrees of freedom. Analogous to the discrete variables case, we call these continuous variable states hybrid-entangled states.

Radially and azimuthally polarized modes can, for example, be described as a superposition of two orthogonally polarized first-order Hermite-Gaussian modes $TEM_{01}$ and $TEM_{10}$. Already in a classical picture these modes display some very intriguing properties. If one calculates the Schmidt-rank of these perfectly classical objects, they have the same tensor-product form of the quantum state of a two-dimensional bipartite maximally entangled system with Schmidt rank 2. This means that already in a classical picture the polarization and spatial degree of freedom are not separable. This effect we call *structural inseparability* and it leads to some very interesting properties when investigating these modes quantum-mechanically.

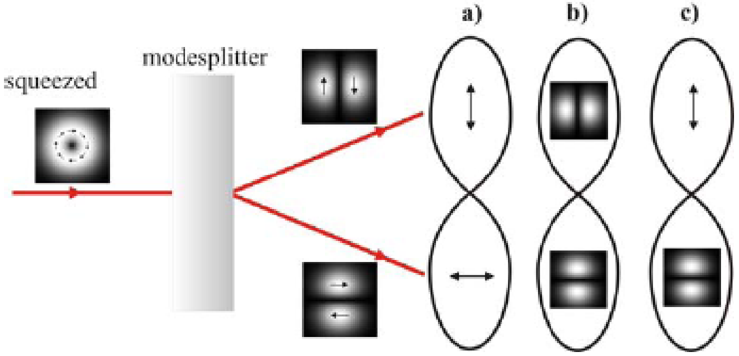

**Figure 1.** *Three types of entanglement are contained in a squeezed azimuthally polarized mode which can be observed by utilizing a mode splitter: (a) polarization entanglement, (b) spatial entanglement, and (c) hybrid entanglement.*

In a quantum-mechanical picture one can define appropriate annihilation and creation operators to describe the cylindrically polarized modes for example in the Hermite-Gauss basis. With the help of these operators one can show that quadrature squeezing of a bright cylindrically polarized mode not only leads to squeezing of its two first-order Hermite-Gaussian basis modes but also to entanglement between these two. Furthermore, we have extended the Duan-Simon criterion for nonseparability to the Stokes parameters for different degrees of freedom in the two spatially separated sub-systems to quantify the entanglement between the two Hermite-Gaussian modes. We have theoretically shown that by quadrature squeezing a cylindrically polarized mode one cannot only measure a) polarization and b) spatial entanglement between these two modes but by measuring the polarization degree of freedom in one arm and spatial degree of freedom in the other arm, one also can c) observe entanglement between these two degrees of freedom (Fig. 1).

In the experiment (Fig. 2a) a mode-locked Ti:sapphire laser, centered at a wavelength of 810 nm and producing 120 fs pulses, acts as a light source. A polarization converter (ARCoptix) is used to generate an azimuthally polarized mode, which is then injected into an asymmetric Sagnac interferometer [8]. The third-order nonlinear Kerr-effect present in a specially designed photonic crystal fiber [9], which maintains the azimuthally polarized mode during propagation, generates quadrature squeezing. For certain input energies this can be detected as amplitude squeezing at the output of the Sagnac loop. This quantum noise reduction is then observed with a direct detection scheme consisting of a detector with sub-shot noise resolution at a radio frequency side band around 10 MHz and a high quantum efficiency silicon photodiode (Fig. 2b). Furthermore, the anticorrelations of the horizontally polarized $TEM_{01}$ mode and the vertically polarized $TEM_{10}$ mode are measured by splitting the azimuthally polarized mode on a polarizing beamsplitter (PBS) and detecting the sum-signal of both outputs of the PBS (Fig. 2c).

With the above described method we have measured 0.6 dB of amplitude squeezing (Fig. 2d). To the best of our knowledge, this is the first time that a quantum noise reduction of a higher-order spatial mode with complex polarization pattern has been observed. Furthermore, 0.5 dB of anticorrelations between the horizontally polarized $TEM_{01}$ mode and the vertically polarized $TEM_{10}$ have been verified (Fig. 2e). These anticorrelations are a good indication that the theoretically predicted entanglement between the different degrees of freedom exists.

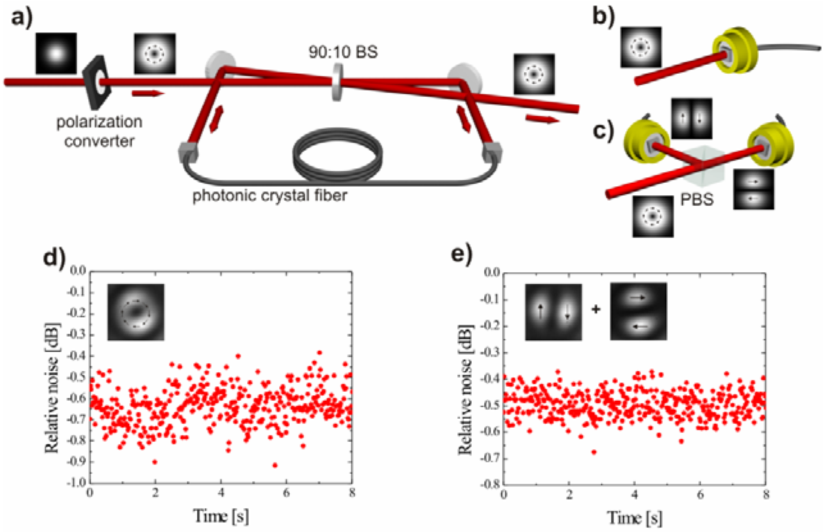

**Figure 2.** *a) Experimental setup. b) and c) the detection systems to observe squeezing and anticorrelations respectively. d) Quantum noise reduction of 0.6 dB achieved for an azimuthally polarized doughnut mode. e) Anticorrelations between the horizontally polarized $TEM_{01}$ mode and the vertically polarized $TEM_{10}$ of 0.5 dB have been measured. The insets in (d) and (e) indicate the measured intensity profiles.*

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**Publications:**

C. Gabriel, A. Aiello, W. Zhong, T. G. Euser, N.Y. Joly, P. Banzer, M. Förtsch, D. Elser, U. L. Andersen, Ch. Marquardt, P. St. J. Russell, and G. Leuchs, *Entangling Different Degrees of Freedom by Quadrature Squeezing Cylindrically Polarized Modes*, Phys. Rev. Lett. **106**, 060502 (2011)

**Conference presentations:**

C. Gabriel, A. Aiello, W. Zhong, A. Holleczek, P. Banzer, M. Förtsch, D. Elser, U. L. Andersen, Ch. Marquardt, and G. Leuchs, *Quantum-Optics with Spatio-Polarization Modes*, 10th International Conference on Quantum Communication, Measurement and Computation (QCMC), July 18-23, 2010, Brisbane, Australia

C. Gabriel, A. Aiello, P. Banzer, M. Förtsch, D. Elser, U. L. Andersen, Ch. Marquardt, and G. Leuchs, *Hybrid-Entanglement in Continuous Variable Systems*, 17th Central European Workshop on Quantum Optics, June 6-11, 2010, St. Andrews, Scotland

C. Gabriel, A. Aiello, P. van Loock, U. L. Andersen, Ch. Marquardt and G. Leuchs, *Generation of multi-partite entanglement between different degrees of freedom by squeezing cylindrically polarized modes*, 12th International Conference on Squeezed States and Uncertainty Relations, May 2-6, Foz do Iguacu, Brazil (2011)

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**Additional progress related to Deliverable 1.1:**
*Nonclassical light in a Whispering Gallery Resonator*
(Partner FAU, DTU)

The generation of squeezed and entangled light is an important resource for quantum computation with continuous variables. In this work we aim at the generation of squeezed and entangled light inside a whispering gallery resonator. Whispering gallery mode (WGM) resonators feature strong optical confinement, small mode volume, and offer tunable coupling to an external optical field [1,2]. With WGM resonators made of nonlinear material one achieves very strong optical nonlinear response, e. g. parametric downconversion (PDC). This process offers a highly wavelength tunable source of light, in particular for quantum optics, where it is used as a state of the art source for nonclassical light [3,4,5]. Driving PDC in cavities, also referred to as an optical parametric oscillator (OPO), provides efficient wavelength conversion. Thus, it is intriguing to investigate PDC in a WGM resonator. Here we present an OPO using a WGM and investigate the quantum properties of the light fields involved for the first time far above the pump power threshold.

In our experiment, the WGM resonator is made of a z-cut Lithium Niobate ($LiNbO_3$) crystal with the optical axis coinciding with the symmetry axis of the WGM cavity. It provides the basis for Type I temperature phase matching for a frequency double Nd:YAG continuous wave laser at 532 nm. Tunable coupling is provided by evanescent overlap with a diamond prism. The cavity is triply resonant with the pump field and the two strongly nondegenerate parametric fields (100 nm apart) with Q-factors in the order of several $10^7$, limited only by internal crystal absorption of the $LiNbO_3$. The pump power threshold of PDC was measured to be around 6.7 µW, which is more than 20 times lower than in previous experiments [6, 7].

The low threshold in combination with continuously adjustable coupling to the WGM resonator, provides large flexibility in setting the ratio between the internal resonator loss rate and the coupling loss rate, dominating the quantum properties of OPOs [9]. In our WGMR OPO, we observed twin-beam correlations of -2.7 dB (see Figure 1), revealing strong coupling dependence. Moreover, the extreme parameters enabled us to directly show for the first time amplitude squeezing of up to -1.2 dB of a single parametric beam in an OPO (see Figure 2). Thus, the quantum correlated twin beams are additionally individually squeezed far above threshold. This opens various possibilities for the use in quantum information. Recently, flexibility in phase matching techniques for WGM OPOs was shown [8]. Driving our WGM OPO below threshold as a narrow linewidth (~10 MHz) single photon source would allow for tuning the parametric beams to convenient wavelength in the visible (atom coupling) and the IR telecommunication band, e. g. for the use in quantum repeaters. In the future, this low threshold would also allow for pumping this WGM OPO with nonclassical light in the first place.

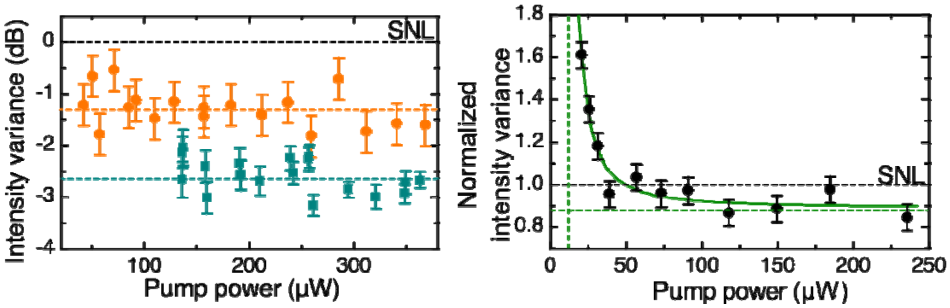

**Fig. 1:** *Left: Twin beam correlations for two different couplings of the WGM resonator (SNL = shot noise limit). Right: Amplitude Squeezing for one single parametric beam (SNL = shot noise limit)*

## References:

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## Publications:

J. U. Fürst, D. V. Strekalov, D. Elser, A. Aiello, U. L. Andersen, Ch. Marquardt, G. Leuchs, *Low-Threshold Optical Parametric Oscillations in a Whispering Gallery Mode Resonator*, Phys. Rev. Lett. **105**, 263904, (2010)

J. U. Fürst, D. V. Strekalov, D. Elser, A. Aiello, U. L. Andersen, Ch. Marquardt, and G. Leuchs, *Quantum Light from a Whispering-Gallery-Mode Disk Resonator*, Phys. Rev. Lett. **106**, 113901, (2011)

## Conference Presentations:

G. Leuchs (invited), "*Squeezed Light from a Whispering Gallery Mode Resonator*", 10th International Conference on Quantum Communication, Measurement and Computation (QCMC), July 18-23, 2010, Brisbane, Australia (2010)

J. U. Fürst, D. V. Strekalov, D. Elser, M. Lassen, U. L. Andersen, Ch. Marquardt, and G. Leuchs, “*Second Harmonic Generation in a Whispering Gallery Mode Resonator*”, DPG, 8 - 12 March 2010, Hannover, Germany (2010)

J. U. Fürst, D. V. Strekalov, D. Elser, U. L. Andersen, A. Aiello, Ch. Marquardt, and G. Leuchs (invited), “*Quantum Light from a Whispering Gallery Resonator*”, 41st winter colloquium on the Physics of Quantum Electronics 2011, Snowbird, Utah, USA (2011)

J. U. Fürst, D. V. Strekalov, D. Elser, U. L. Andersen, A. Aiello, Ch. Marquardt, and G. Leuchs, “*Quantum Light from a Whispering Gallery Resonator*”, DPG, 13 – 18 March 2010, Dresden, Germany (2011)

J. U. Fürst, D. V. Strekalov, D. Elser, U. L. Andersen, A. Aiello, Ch. Marquardt, and G. Leuchs, “*Low-threshold Optical Parametric Oscillations in a Whispering Gallery Mode Resonator*” in Conference on Lasers and Electro-Optics Europe / European Quantum Electronics Conference, Technical Digest (European Physical Society, 2009), Munich, CD11.1 THU (2011)

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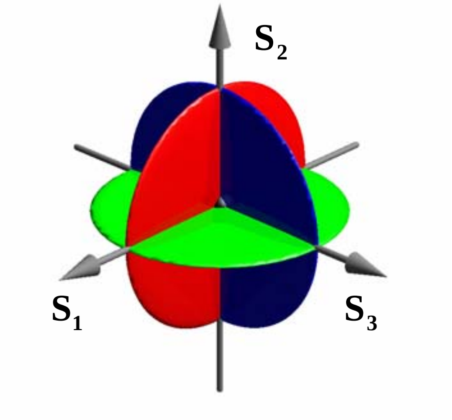
## Additional progress related to Deliverable 1.1:
*Macroscopic analog of the singlet two-photon Bell state*
(Partner FAU)

We have produced a bright state of light that, although being pure, is completely unpolarized. Also known as polarization-scalar light, it is the macroscopic analog of the singlet two-photon Bell state (MSBS). Surprizingly, it has photon numbers in two orthogonal polarization modes exactly equal regardless of the choice of these modes. Therefore both the mean values and the noise of all Stokes observables are, ideally, zero (black point at the origin). For each of the other three macroscopic Bell states, forming *the triplet*, noise is suppressed only for one polarization observable (coloured disks). The MSBS is interesting as a possible candidate for macroscopic Bell tests or for noiseless measurements of material optical anisotropy.



In experiment, MSBS was obtained by superposing two coherent orthogonally polarized two-color squeezed vacuums (SV). Since two-mode SV manifests absolute correlation between photon numbers in conjugate beams at any parametric gain, this technique allows one to prepare macroscopic quantum states of light. The obtained results for MSBS demonstrate 30% noise reduction below shot-noise level for all Stokes observables.

**Publications:**

I. N. Agafonov, M. V. Chekhova, and G. Leuchs, *Two-Color Bright Squeezed Vacuum*, Phys. Rev. A 82, 011801(R) (2010).

T. Sh. Iskhakov, M. V. Chekhova, G. O. Rytikov, and G. Leuchs, *Macroscopic Pure State of Light Free of Polarization Noise*, Phys. Rev. Lett. 106, 113602 (2011).

**Conference Presentations:**

A. N. Agafonov, M. V. Chekhova, T. Sh. Iskhakov, and G. Leuchs, *Macroscopic squeezed vacuum and its direct detection*, Quantum 2010: V Workshop ad memoriam of Carlo Novero ‘Advances in Foundations of Quantum Mechanics and Quantum Information with atoms and photons’ (IQIS 2010), 23-29 May 2010, Turin, Italy (invited).

M. V. Chekhova, I. N. Agafonov, T. Sh. Iskhakov, and G. Leuchs, *Bright Squeezed Vacuum*, 17th Central European Workshop on Quantum Optics (CEWQO), St. Andrews, Scotland, UK, 6th-11th June, 2010 (oral).

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I. N. Agafonov, M. V. Chekhova, T. Sh. Iskhakov, G. Leuchs, *Two-color bright squeezed vacuum*, 19th International Laser Physics Workshop (LPHYS’10), Foz do Iguaçu, Brazil, July 5-9, 2010 (poster).

## **Task 1.2**: Exploring models of CV quantum computing

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

**Status:** Due month 24; Delivered on time. Additional progress reported.

**Partners:** ULB, UP, POTSDAM

Although this task had been completed at month 24, some additional progress has been realized during the third period on other possible models of CV quantum computing. In particular, ancilla-driven quantum computation has been introduced by USTAN. It is, in some settings, similar to one-way or cluster computing but not equivalent to it. Another potential model for universal quantum computation has also been investigated by USTAN that is using continuous-variable abelian anyons. A model for measurement-based quantum computing based on gapped Hamiltonian systems in the continuous-variable domain has been proposed by ICFO. Then, a scheme for quantum bit commitment that is based on non-Gaussian light states has been proposed by ULB. Finally, some general study has been carried out by POTSDAM on what class of continuous-variable quantum states can be used in order to perform efficient measurement-based quantum computing.

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### Additional progress related to Deliverable 1.2:

*Ancilla-driven quantum computation*

(Partner USTAN)

We extend the recently suggested ADQC (ancilla-driven quantum computation) computation model [1] to the continuous-variable regime [2] and to hybrid CV/DV setting, e. g., superconducting qubit register interacting with a photonic ancilla mode. In the ADQC model, manipulating a quantum register is accomplished remotely, with the help of a fully controlled ancilla qubit (or in our case, a continuous variable photonic mode, similar as in the quantum bus proposals). Thus there is no direct manipulation of register involved. The ancilla is coupled to the register via fixed unitary two-qubit interaction and then measured, thus the actual qubit remains largely untouched (only addressed with a single coupling operation and no measurement is applied). The whole computational process is driven by manipulating the ancilla alone.

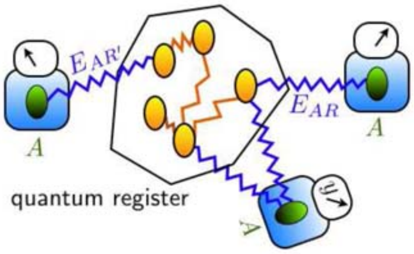

**Fig. 1.** *Illustration of ancilla-driven quantum computation [1]. The system of quantum registers and the ancille, A, are coupled together with a single and fixed ancilla-register interaction* $E_{AR}$ *and the ancilla is measured on some basis.*

ADQC is also naturally hybrid. A suitable system to implement this model hence consists of long-lived but static qubits (e.g., solid state qubits) addressed by mobile ancilla. We suggest using for the latter a photonic mode and the model has to be extended to take into account the continuous variable version of the ancilla. Largely like in the quantum bus scheme, the measurements will be performed using either homodyne or photon number detection. We have translated the ADQC model for continuous variable quantum computation [2] and the work on the hybrid model is in progress. We have shown that the continuous-variable analogue, CV ADQC is universal. With currently available optical tools in the lab, one can implement any multimode Gaussian transformation with the scheme devised in [2]. However the non-Gauusian element required for universality is not experimentally available yet.

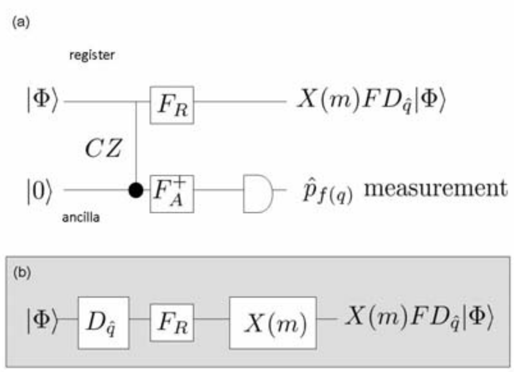

**Fig. 2.** *CV ADQC: (a) Implementation of* $E_{AR}$ *followed by the ancilla measurement on in momentum basis. (b) Equivalent circuit for the register input state. It implements one of the Clifford gates followed by Fourier transform gate with a measurement dependent displacement X(m).*

The advantage of the ADQC model is a prospect for better scalability, as the computational register can be separated from state preparation and measurement, and thus does not require challenging tailored control. The problem of register qubits decoherence is also relaxed, in particular in the systems where measurements would be destructive.

**Publications:**

[1] J. Anders, D. K. L. Oi, E. Kashefi, D. E. Brown, E. Andersson, *Ancilla-Driven Quantum Computation*, Physical Review A 82, 020301(R) (2010).

[2] T. Nakano, E. Andersson, N. Korolkova, *Ancilla-driven quantum computation for continuous variables*, manuscript in preparation (2010)

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**Additional progress related to Deliverable 1.2:**
*Topological quantum computation using CV abelian anyons*
(Partner USTAN, FAU)

A recent development in the field of quantum error correction is the realization of certain two-dimensional states that support quasi-particle excitations known as anyons. It has been shown that certain species of anyons can be utilized for topological quantum computation which offers intrinsic protection for quantum states from local errors caused by decoherence by storing information as a global property of the physical system. It has been suggested that anyons will manifest at certain filling fractions in Fractional Quantum Hall Systems (FQHS), however these have proved difficult to access experimentally. Recent proposals have shown that anyonic statistics can be simulated on the surface of two-dimensional spin lattices, so called Kitaev lattices, and discrete-variable encodings and computational models have been suggested for these models.

We have extended these ideas by describing how continuous-variable (CV) abelian anyons, created on the surface of CV analogues of Kitaev's lattice model (Fig. 1) can be utilized for CV quantum computation. In particular, we have classified the set of quantum gates possible to implement using topological operations alone. However we found that this gate set is insufficient for universal quantum computation which led us to study additional non-topological operations such as offline squeezing and single mode measurements. It was shown that these in conjunction with a non-Gaussian element allow for universal quantum computation using continuous-variable abelian anyons.

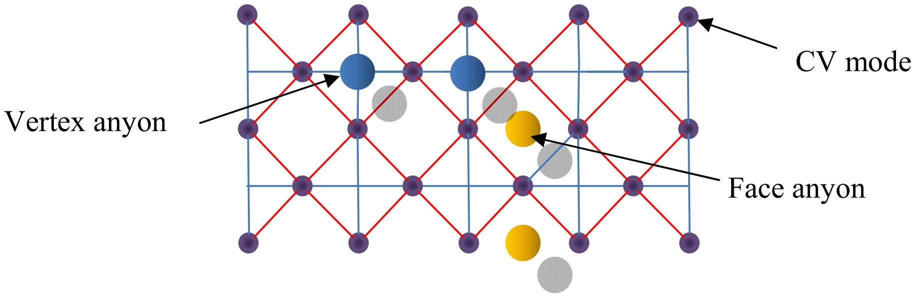

**Fig 1.** *CV analogue of Kitaev's lattice model*

Following on from this, we have shown the same lattice can support non-abelian excitations which we identify as CV analogues of Ising anyons. These CV Ising anyons are constructed from super-positions of the CV abelian anyons. We found that the fusion and braid rules generate a generalized version of the discrete Ising model (Fig. 2). We then show how to encode qubit in the the CV Ising anyons states and develop a universal computational model using topological operations only. Hence we show that universality for qubit computation can be realised from topologically protected continuous variable resources.

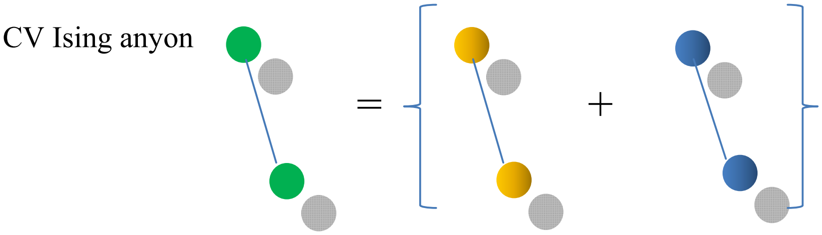

**Fig 2**. *CV Ising anyons constructed from super-positions of the CV abelian anyons.*

Furthermore, we have extended our treatment to include finite squeezing of the Kitaev ground state. Excitations on the surface of these finite squeezed CV lattices correspond to Gaussian anyons. We have shown that braiding and fusion operations on these finitely squeezed Gaussian anyons produce extra topological phase factors dependant on the degree of squeezing on the ground state. However these extra phases are always known and can be corrected for, so we have shown that topological operations are always protected from the errors due to finite squeezing.

**Publications:**

D. F Milne, N. V Korolkova, P. van Loock, *Universal Quantum Computation with Continuous-Variable Abelian Anyons* (Manuscript)

D. F Milne, N. V Korolkova, P. van Loock, *Continuous-Variable non-Abelian anyons from an Abelian anyon model* (Manuscript)

**Conference Presentation:**

D. F Milne, N. V Korolkova, P. van Loock, *"Universal Quantum Computation with Continuous-Variable Abelian Anyons",* Poster accepted, 11th Canadian Summer School on Quantum Information, June 6-17th 2011, Centre de Villégiature de Jouvence, Québec, Canada.

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**Additional progress related to Deliverable 1.2:**
*Gapped two-body Hamiltonian for continuous-variable measurement-based quantum computation* (Partner ICFO)

Measurement based quantum computation (MBQC) represents a model for quantum computation alternative to the circuit model, in which computation proceeds by a sequence of gates (unitary operations) applied to an initial quantum register. In MBQC, the quantum computation proceeds as a sequence of local adaptative measurements on a multi-particle entangled state, the cluster state. The special entanglement properties of this state make quantum computation possible. Actually, it was later understood that there are other multi-particle entangled state, apart from the cluster state, which allow this form of quantum computation. Moreover, although the model was initially proposed for discrete-variable systems, MBQC and the cluster state were later generalized to the continuous variable regime.

Apart from its conceptual interest, MBQC also offers a different approach for the implementation of quantum computation. Indeed, it is possible to engineer the interactions among many particles in such a way that the resulting Hamiltonian has a ground state equal to cluster state. Quantum computation can then be performed as follows: (i) the cluster state is prepared either by cooling the system, or by adiabatic evolution from another ground state and (ii) local measurements are applied to the resulting state, obtaining the result of the quantum computation. This explains why there has been a theoretical effort to identify experimentally friendly Hamiltonians whose ground state is the cluster state, or any other state universal for quantum computation. All this effort has been devoted to discrete-variable systems. However, no such Hamiltonian has been reported for the continuous-variable domain.

Our main result is to provide a family of Hamiltonian systems for MBQC with continuous variables. The Hamiltonians (i) are quadratic, and therefore two body, (ii) are of short range, (iii) are frustration-free, and (iv) possess a constant energy gap proportional to the squared inverse of the squeezing. We show that their ground states are the celebrated Gaussian graph states, which are universal resources for quantum computation in the limit of infinite squeezing. Moreover, we characterize the correlations in these systems at thermal equilibrium. The obtained Hamiltonians constitute the basic ingredient for the adiabatic preparation of graph states and thus open new venues for the physical realization of continuous-variable quantum computing beyond the standard optical approaches. Indeed, the basic constituents of these Hamiltonians have already been demonstrated in technologically mature experimental platforms, as Coulomb crystals and opto-mechanical resonators. In addition, this type of couplings have also been envisioned in coupled-micro-cavities arrays or superconducting waveguides. All these constitute examples of versatile and promising architectures where controlled geometrical arrangements of the desired interactions seem feasible in a very near future.

**Publication:**

Leandro Aolita, Augusto J. Roncaglia, Alessandro Ferraro, Antonio Acín, *Gapped Two-Body Hamiltonian for continuous-variable quantum computation*, Phys. Rev. Lett. 106, 090501 (2011).

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**Additional progress related to Deliverable 1.2:**
*Quantum Bit Commitment under Gaussian Constraints*
(Partner ULB)

Quantum bit commitment (QBC) is probably one of most studied quantum cryptographic primitive, just after quantum key distribution. It belongs to the class of mistrustful cryptography problems, which involve two parties (Alice and Bob) who do not trust each other. More specifically, it is a primitive in which Alice commits to a certain bit while this bit should remain hidden to Bob until Alice later reveals its value. Unfortunately, QBC has long been known to be impossible, or more precisely it cannot be both perfectly concealing and binding (see, e.g., {1}). Nevertheless, it was realized later that, just as in the classical case, if certain restrictions are imposed on the operations available to the parties, a QBC may be constructed that is secure or at least partially secure.

During the third year of the project, partner ULB has devised a continuous-variable QBC protocol based on quantum states of light lying in an infinite-dimensional Hilbert space. This quantum optical protocol (see Figure 1) is based on the hypothesis that Alice is restricted to carry out Gaussian operations only, which is consistent with the current experimental ability to engineer quantum states of light in a deterministic way. As a matter of fact, all the experiments that have been successful in preparing and manipulating non-Gaussian states of traveling light states are based on heralded photon subtraction or addition, hence are probabilistic in nature. Note that many of these experiments have been realized within the projects COVAQIAL and COMPAS, see e.g. {2,3,4}. A deterministic scheme would require high optical nonlinearities that are not accessible in the laboratory today. Since probabilistic cheating does not endeavor the security of QBC if the success probability is low (this even holds true otherwise, though in the asymptotic protocol only), such a restriction to Gaussian cheating operations is justified in the context of QBC.

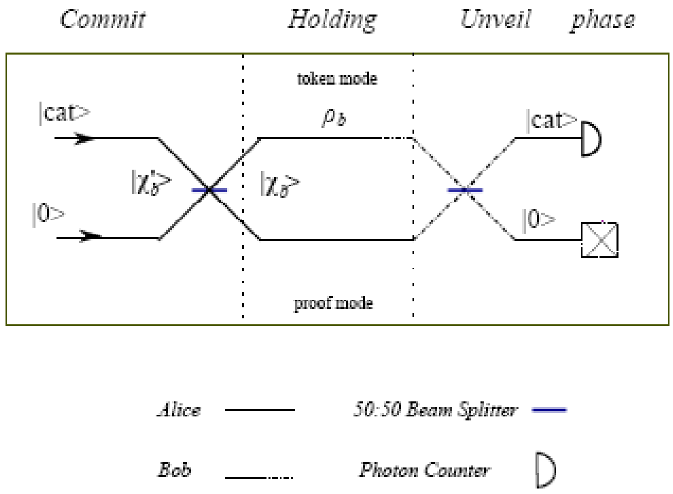

**Figure 1:** *Quantum bit commitment protocol based on cat states of light. The committed state can either be an even or an odd cat state of amplitude α' depending on the bit b to be committed. The token mode is transmitted in the commit phase, while the proof mode is transmitted in the unveil phase. Bob combines the two modes at a balanced beam splitter and measures the photon number parity in the first mode.*

Thus, although it is not impossible, in principle, to realize deterministic non-Gaussian optical operations based on giant nonlinearities, there is a natural boundary separating the Gaussian from non-Gaussian deterministic operations, and it is experimentally relevant to investigate a QBC scenario where Alice is not allowed to carry out non-Gaussian cheating operations. This scenario had been introduced by partner ULB during the first year of the project, and a strong *no-go theorem* was derived {5}: secure quantum bit commitment is forbidden in continuous-variable protocols where both players are restricted to use Gaussian states and operations. In other words, if the protocol is built on Gaussian states, it is sufficient for the players to carry out Gaussian operations in order to cheat perfectly. Circumventing this no-go theorem, partner ULB has thus proposed during the third year of the project an explicitly non-Gaussian QBC protocol based on cat states of light but with Gaussian constrained cheating. The fact that this QBC protocol is asymptotically secure is apparent in Figure 2.

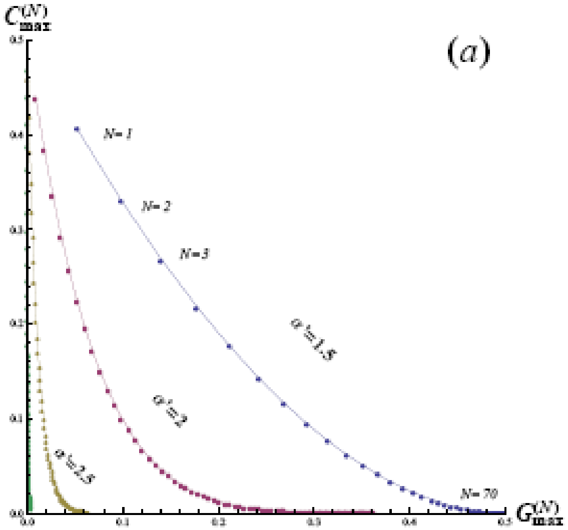

**Figure 2:** *Alice's maximum control* $C_{max}^{(N)}$ *versus Bob's maximum information gain* $G_{max}^{(N)}$ *for different amplitudes α' of the cat state. We see that a specific constraint on Alice's cheating operations which is experimentally well motivated gives rise to an asymptotically secure QBC protocol since, for sufficiently large values of α', both parameters* $C_{max}^{(N)}$ *and* $G_{max}^{(N)}$ *tend to zero.*

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**Publications:**

A. Mandilara and N. J. Cerf, *Quantum Bit Commitment under Gaussian Constraints*, arXiv:1105.2140; submitted to Physical Review A.

A. Mandilara and N. J. Cerf, *Bit commitment under constraints in classical and quantum world*, Proceedings of the 32nd WIC Symposium (2011).

**Conference presentations:**

*Quantum Bit Commitment under Gaussian Constraints* (poster), A. Mandilara and N.J. Cerf. 12th International Conference on Squeezed states and Uncertainty relations and 5th Feynman Festival, 2-5 May 2011, Foz do Iguacu, Brazil.

*Quantum Bit Commitment under Gaussian Constraints* (contributed talk), A. Mandilara and N.J. Cerf. Joint WIC/IEEE SP Symposium on Information Theory and Signal Processing in the Benelux, May 8, 2011, Brussels. Belgium.

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**Additional progress related to Deliverable 1.2:**
*Classification of non-Gaussian resources for measurement-based quantum computing*
(Partner POTSDAM)

An extensive investigation of the potential and limitations of continuous-variable measurement-based quantum computing had already been reported at month 24, completing Task 1.2; yet a number of key questions have been left open, which have now been settled in quite some generality. Work done in the third year clarifies - within a general class of states generalizing matrix-product states - what continuous-variable quantum states can be used in order to perform efficient measurement-based quantum computing [1].

This research seems particularly timely in the light of the no-go-results that could be achieved in the last year, pointing towards the necessity of using non-Gaussian states in the first place (the latter work has in the meantime been published in a journal [2]). We have now been able to classify resources, and by doing that, also able to present schemes for continuous-variable quantum computing that are strictly efficient and for which even notions of fault tolerance and error corrections are applicable [1]. The physical feasibility of the schemes is described in great detail.

**Publications:**

[1] M. Ohliger and J. Eisert, in preparation (2011).
[2] M. Ohliger, K. Kieling, and J. Eisert, *Phys Rev A* **82**, 042336 (2010).

## Task 1.3: Engineering non-Gaussian states of light

**Deliverable 1.3:** ***Generation of high photon number Fock states***
**Status:** Due month 24; Intermediate progress reported at months 12 and 24; Delivered.

**Deliverable1.4:** ***Generation of monomode and multimode cat states***
**Status:** Due month 24; Intermediate progress reported at months 12 and 24; Delivered.

**Partners:** CNRS/IO

Some significant achievements related to the generation of non-Gaussian states of traveling light (towards Deliverable 1.3 and 1.4) had been reported previously by partner CNRS/IO, in particular the generation of non-local superpositions of quasi-classical light states (non-local "cat" states) based on non-local photon subtraction. This has been completed during year 3 with the experimental demonstration of non-Gaussianity resulting from photon addition by partner CNRS/IO. The experimental demonstration of non-Gaussian states by photon subtraction from squeezed vacuum has also been carried out by partner DTU using picosecond pulsed pump laser.

The generation of high photon number Fock states via conditional multiphoton detection was experimentally assessed in detail by partner CNRS/IO during the first and second years of the project. The conclusion was that the available photon-number resolving detectors are currently not suitable for the task. Since the generation of Fock states was only an auxiliary step towards the preparation of cat states, it was decided to focus on mastering the single photon addition. This operation, combined with photon subtraction, fully opens the way towards the engineering of non-Gaussian states of light. It can, for instance, be used to noiselessly amplify the experimentally available kitten states to large cat states. The goals of Deliverables 1.3 and 1.4 therefore become largely interconnected after this change of strategy, and it was deemed irrelevant to keep them separate. The progress reported below is therefore jointly associated with both Deliverables 1.3 and 1.4, which are thus delivered together.

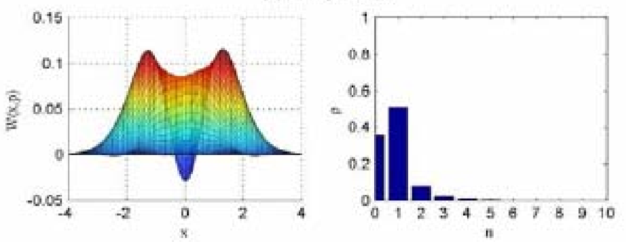
### Reported progress towards Deliverables 1.3 and 1.4:

*Experimental generation of non-Gaussian states by photon subtraction from squeezed vacuum*
(Partner DTU)

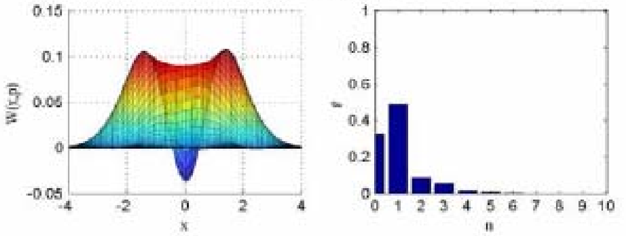
As a preliminary step to the implementation of the Hadamard gate presented in Task 31 (Deliverable 3.2), partner DTU has implemented a system to generate coherent state superpositions (cat states) based in single photon subtraction from squeezed vacuum. In contrast to previous implementations, partner DTU has employed pico-second pulsed light as an energy source for the system. Using such pulses, the states are well-defined in time (in contrast to experiments based on a CW source) and one largely circumvents issues with group velocity dispersion (as opposed to experiments with femto-second pulses).

Squeezed vacuum states are produced in a periodically poled KTP crystal. These states are directed to an asymmetric beam splitter that reflects 7% of the light towards a train of spatial and temporal filters and an APD. Upon detection of a single photon, the state is projected onto single photon subtracted squeezed state which is finally fully characterized using homodyne tomography. This experiment is repeated with four different degrees of squeezing (associated with four different pump powers), and the results are illustrated in Fig. 1. Here the Wigner functions and the photon number distributions for the resulting output states are shown.

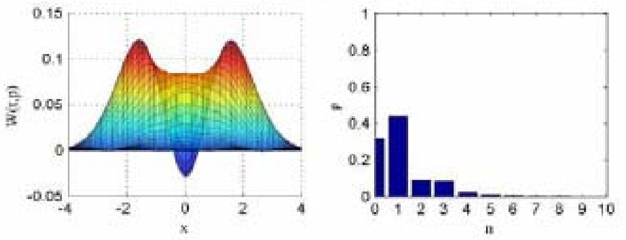
(a) Pump: 1mW



(b) Pump: 2mW



(c) Pump: 4mW



(d) Pump: 6mW

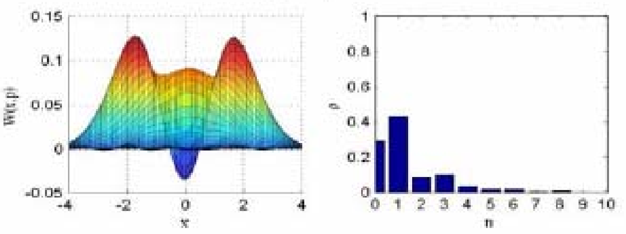


***Fig. 1.*** *Wigner functions and photon number distributions for the single photon subtracted squeezed states for different pump powers varying from 1mW to 6mW.*

## Conference presentations:

*Continuous Variable Quantum Communication and Computation*, Ulrik L. Andersen, Anders Tipsmark, Ruifang Dong, Amine Laghout, Miroslav Jezek, CLEO, The Conference on Lasers and Electro-Optics, Baltimore convention center, Baltimore, Maryland, USA, 1-6 May 2011. INVITED TALK.

*Quantum Information Processing with Discrete and Continuous Variables*, Ulrik L. Andersen, Anders Tipsmark, Ruifang Dong, Amine Laghout, Miroslav Jezek, International Conference on Quantum Information (ICQI), June 6-8 2011, Uni. of Ottawa, Canada. INVITED TALK.

**Reported progress towards Deliverables 1.3 and 1.4:**

*Non-Gaussianity of quantum light states by single- photon addition on coherent states*

(Partner CNRS/IO)

The synthesis of non-Gaussian states is one main feature of measurement-induced nonlinear operations. A measure of the degree of non-Gaussianity of quantum states would therefore be a helpful tool for the characterization of measurement-induced processes. We tested a new measure of non-Gaussianity, introduced in [1,2], on an important class of non classical states, single-photon added coherent states. Photon addition can be performed using non-degenerate optical parametric amplifier, where the input state (here a coherent state) is injected into the input of the signal mode, and where photon addition is trigged by a photon detection event in the idler output (see figure below).

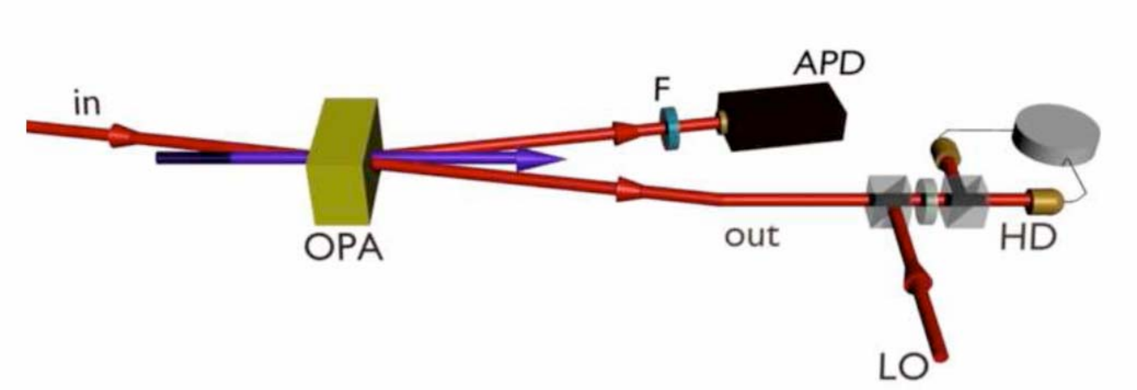


***Figure 1:*** *Experimental setup. The photon addition is trigged by a detection event on an avalanche photodiode (APD). The tomography of the output state is performed by homodyne detection (HD).*

Our non-Gaussianity measure $\delta[\rho]$ is defined as the quantum relative entropy between the quantum state itself $\rho$ and a reference Gaussian state $\tau$ having the same covariance matrix as $\rho$. This measure can be easily evaluated from experimental data. The figure below (left panel) presents results obtained for $\delta[\rho]$ for different values of the amplitude $\alpha$ of the input coherent state. These results are compared (right panel) to a quantity $\nu[\rho]$ related to the non-classicality of the state, defined as the minimum (negative) value of the Wigner function normalized to the corresponding value for an ideal one-photon state as a reference.

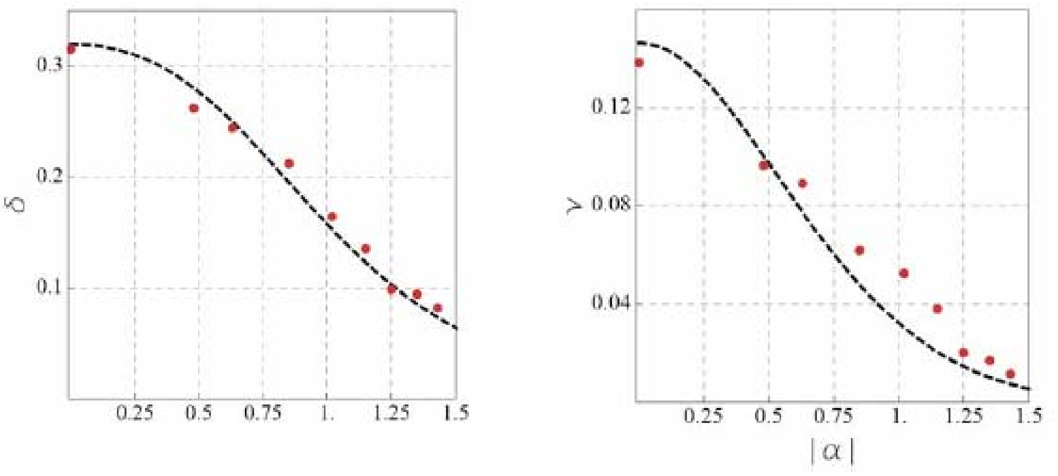


***Figure 2:*** *(left panel) experimental value (red points) of the non-Gaussianity measure as a function of the coherent state amplitude* $\alpha$*. (right panel) non-classicality measure* $\nu$*.*

These experiments on single-photon added coherent states demonstrate the relevance of this recently proposed measure of the non-Gaussianity. This measure appears as a reliable and sensitive way to quantifying experimental imperfections of de-Gaussification experiments. It furthermore allows to exhibit a link between non-Gaussianity and non-Classicality in such experiments.

**References:**

[1] M. G. Genoni, M. G. A. Paris and K. Banaszek, Phys. Rev. A 78, 060303(R) (2008).
[2] M. G. Genoni and M. G. A. Paris, arXiv:1008.4243v2 [quant-ph]

**Publications:**

M. Barbieri, N. Spagnolo, M. G. Genoni, F. Ferreyrol, R. Blandino, M.G.A. Paris, P. Grangier, and R. Tualle-Brouri, *Non-Gaussianity of quantum states: an experimental test on single-photon added coherent states*, Phys. Rev. A **82**, 063833 (2010).

**Conference / Poster presentations**

F. Ferreyrol, R. Blandino, M. Barbieri, R. Tualle-Brouri, and P. Grangier, "*New adventures in non-Gaussian space*", Conférence invitée, 19th International Laser Physics Workshop, Foz do Iguaçu (BR), July 4th-9th (2010).

P. Grangier, "*Quantum information with continuous variables*", Conférence invitée, International Conference on Quantum Communication, Measurement and Computation (QCMC), Brisbane, Australie, 19- 23 juillet 2010 (2010).

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

**Deliverable1.5:** ***Measurement-induced nonlinear operations***
**Status:** Due month 36; Delivered in advance at month 24; Additional progress reported.

**Deliverable 1.6:** ***Detector process tomography***
**Status:** Due month 24; Delivered at month 24; Additional progress reported.

**Partners:** CNRS/IO, ULB, UP, POTSDAM

The experimental demonstration of the heralded noiseless amplification of light (a paradigmic example of a measurement-induced operation) has been carried out by partner CNRS/IO during the second year, leading to Deliverable 1.5 in advance. During the third year, the high-fidelity probabilistic noiseless amplification of light has also been demonstrated by partner UP in collaboration with the group of Prof. Bellini. This concept has been pushed further by partner FAU with the demonstration of noise-powered concentration of phase information based on this noiseless amplifier. This probabilistic scheme for the enhancement of coherent state phase information consists of a random displacement followed by heralding based on a photon number resolving measurement. Other measurement-induced processes have also been investigated by partner USTAN, while partner POTSDAM has further worked on Deliverable 1.6 and introduced continuous-variable quantum compressed sensing. This is all reported here as extra progresses related to D1.5 and D1.6.

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### Additional progress related to Deliverable 1.5:

*High-fidelity probabilistic noiseless amplification of light*
(Partner UP)

Fundamental laws of quantum mechanics impose that arbitrary quantum states cannot be perfectly cloned or amplified without introducing some unavoidable noise in the process. The quantum noise intrinsic to the functioning of a linear phase-insensitive amplifier can however be avoided by relaxing the requirement of a deterministic operation. Non-deterministic noiseless linear amplifiers that do not violate any fundamental quantum law are therefore possible. Partner UP in collaboration with the group of Professor Marco Bellini at INOA, Florence experimentally implemented a scheme that allows noiseless amplification of coherent states of light at the best level of effective gain and final state fidelity ever reached. This noiseless quantum amplifier with nominal gain g=2 is based on a sequence of photon addition and subtraction.

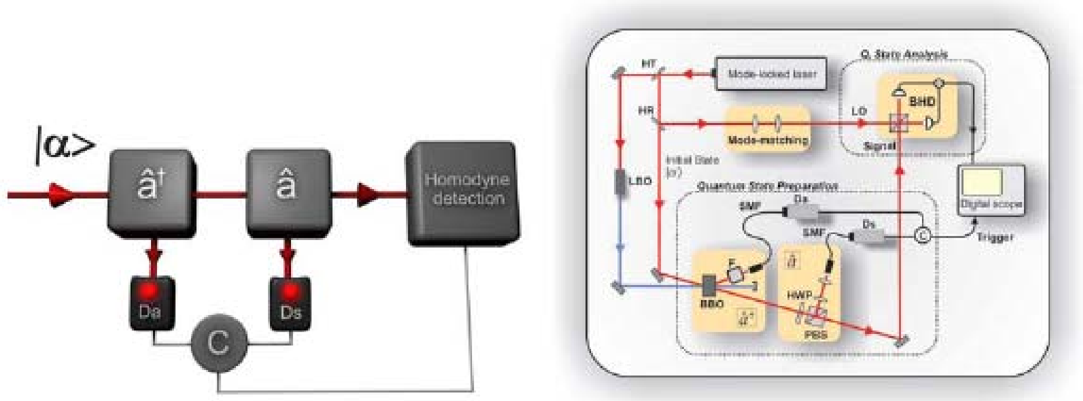

**Fig. 1:** *Conceptual scheme (left) and detailed experimental setup (right). Da and Ds denote single photon detectors, HT (HR) is a high transmissivity (reflectivity) beam splitter; LBO is a lithium triborate crystal for frequency doubling; SMF are single mode fibers; F is a narrow spectral filter.*

The experimental setup is shown in Fig. 1. Two blocks for conditional single-photon addition and subtraction are placed in the path of a coherent state. A coincident click (C) from the two on/off photo-detectors Da and Ds heralds the successful realization of the probabilistic noiseless amplification of the input coherent state. High-frequency, time-domain, balanced homodyne detection is then used for a full reconstruction of the involved quantum states. The amplifier was thoroughly characterized for a range of input coherent states with amplitude up to α=1. In particular, we have determined the effective gain of the amplifier, quadrature variances, and fidelity of the amplified state. The results displayed in Fig. 2 confirm that the amplifier exhibits high gain and fidelity and adds only very little noise.

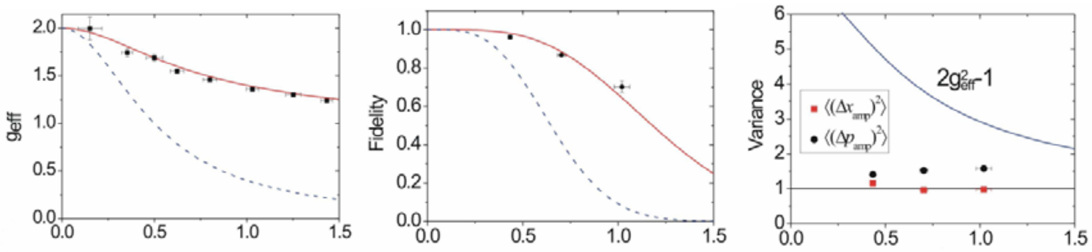

**Fig. 2***: Dependence of the effective gain (left) and final state fidelity (center) on the input coherent state amplitude* $|\alpha|$. *Red solid curves are calculated for the addition/subtraction scheme; blue dashed curves are for the amplification based on quantum-scissors method; square dots indicate experimental data. Right panel displays measured variances of the amplitude and phase quadratures of the amplified coherent state and the corresponding (blue solid) curve for the best deterministic amplifier.*

The demonstrated noiseless amplifier can compensate for losses in quantum communication schemes and can be used to distill and concentrate entanglement. Since it preserves quantum coherence it could be used for breeding small cat-like states formed by superposition of two coherent states, which may greatly facilitate quantum computing with cat-state qubits. An extended interferometric version of the setup can be used to perform amplification with tunable gain and also emulate Kerr nonlinearity thus providing novel means to implement quantum gates on states of light. Feasibility of the interferometric scheme has been very recently confirmed in preliminary experimental tests employing inherently stable configuration that exploits polarization degree of freedom instead of two different spatial paths.

**Publications:**

Zavatta, J. Fiurášek, and M. Bellini, *A high-fidelity noiseless amplifier for quantum light states*, Nature Photonics **5**, 52–56 (2011).

A. Zavatta, M. Locatelli, C. Polycarpou, J. Fiurášek, and M. Bellini, *High-fidelity noiseless amplification by photon addition and subtraction*, Proc. SPIE **8072**, 80720P (2011).

**Conferences:**

J. Fiurášek, A. Zavatta, M. Bellini, *Engineering quantum operations on traveling light beams by multiple photon addition and subtraction*, XIII International Conference on Quantum Optics and Quantum Information (ICQIO'2010), Kiev, Ukraine, May 28 – June 1, 2010.

J. Fiurášek, P. Marek, R. Filip, A. Zavatta, M. Bellini, *Engineering quantum operations on traveling light beams*, 17th Slovak-Czech-Polish Optical Conference: Wave and Quantum Aspects of Contemporary Optics, Liptovský Ján, Slovakia, September 6-10, 2010.

J. Fiurášek, A. Zavatta, M. Bellini, *High-fidelity noiseless amplification of light,* Ensemble-Fest 2011, ICFO, Barcelona, Spain, January 14, 2011.

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**Additional progress related to Deliverable 1.5:**
*Noise-powered concentration of phase information*
(Partner FAU)

Deterministic amplification of an unknown quantum state is a process inevitably linked to the addition of excess noise [1,2]. In particular the phase information carried by the state gets degraded in the amplification process. However, noiseless amplification can in principle be achieved by releasing the constraint of determinism [3]. Recent experiments [4-6] were challenging as they were relying on high interferometric stability, multiple single photon sources or high-order non-linear interactions, making the implementation hardly feasible. Therefore we demonstrate in this year's report a scheme capable of probabilistically increasing the phase information of coherent states based on the addition of thermal noise prior to a weak photon number resolving measurement. Surprisingly, this scheme benefits from the additional noise, usually detrimental to quantum protocols.

A sketch of the scheme is shown in Fig.1. A coherent state with unknown phase entering the setup is mixed with thermal noise. It is subsequently split asymmetrically into two parts. The weaker part is sent to a photon number resolving detector PNRD, where it provides the information used to herald the output state. The brighter part is sent to a gate, that can be passed, when the number of clicks in the detector equals or surpasses a given threshold value M. The heralding procedure thereby exploits the classical correlations between the transmitted and tapped-off part of the beam, that have been introduced by the addition of thermal noise. A high number of detections in the tap beam is correlated to a high amplitude in the transmitted beam

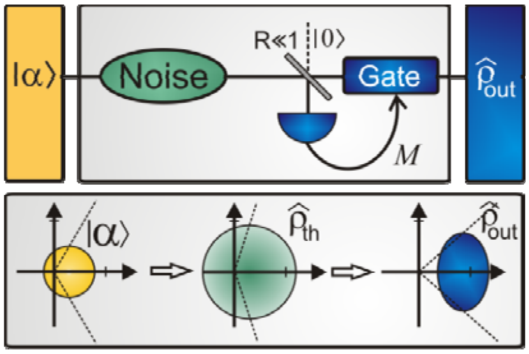

**Fig. 1:** *(top) Sketch of the scheme. First, the input coherent state is mixed with thermal noise. A small portion of the state is measured and the remaining part is heralded according to the outcome of the measurement. (bottom) Evolution of the coherent state during the phase concentration cycle. The heralding on high number of detections leads to an effectively amplified state with decreased phase variance, as indicated by the dashed lines.*

We verified the increase of phase information in an experimental implementation by homodyne tomography of the heralded states for threshold values of up to four clicks in the detector. We derived the Holevo phase variance [7] as a measure for the phase uncertainty and compared the results for various threshold parameters with our theoretical model [8]. We could clearly observe the enhanced phase information, yet for a threshold of only a single click in the detector, as presented in Fig.2.

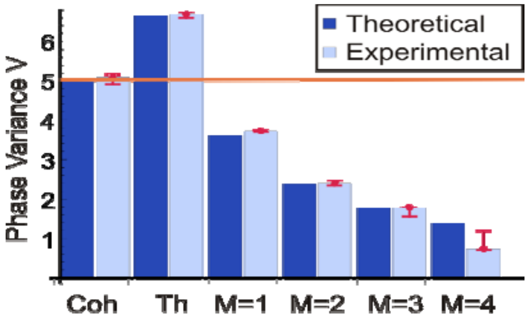

**Fig. 2:** *Experimental and theoretical results for the phase variance of the input coherent state (Coh), the input state after the mixing with thermal noise (Th) and the heralded output states (M=1, ..., M=4). Enhanced phase information is already observed for a heralding threshold of just a single click in the detector.*

To further visualize the action of the scheme, we have reconstructed the Wigner functions of the input state as well as for the output state at different threshold values. The results are shown in Fig.3. It can be seen, that the heralded states have a broader width compared to the coherent input, however theses states also have an increased amplitude, such that the phase information is enhanced.

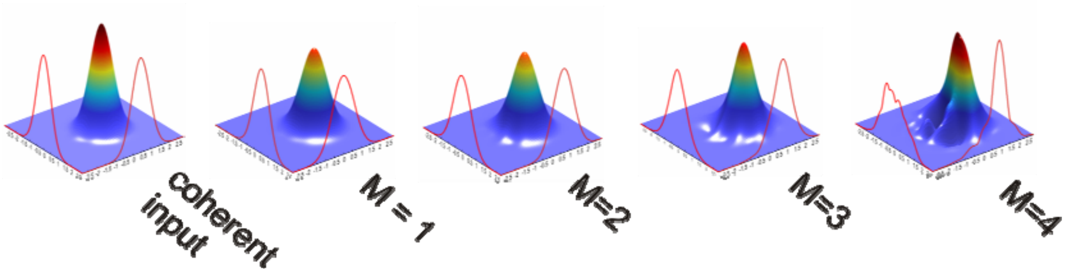

**Fig.3:** *Wigner functions and marginal distributions (red lines) of the heralded states for up to four clicks in the detector.*

**References:**

[1] Haus, H.A. and Mullen J.A. , Phys. Rev. **128**, 5 (1962)
[2] Caves, C.M., , Phys. Rev. D, **26**, 8 (1982)
[3] Ralph, T.C. and Lund, A.B., QCMC Proc. of 9th Int.Conf. 155-160 (2009)
[4] Xiang, G. Y. et al., Nat. Phot. **4**, 316 - 319 (2010)
[5] Ferreyrol, F. et al., Phys. Rev. Lett. **104**, 123603 (2010)
[6] Zavatta, A. et al., Nat. Phot. **5,** 52-60 (2011)
[7] Holevo, A.S., Lect. Notes in Math., **1055**, 153-172 (1982)
[8] Marek, P. and Filip, R., Phys. Rev. A, **81**, 022302 (2010)

**Publications:**

M. A. Usuga, C. R. Müller, C. Wittmann, P. Marek, R. Filip, Ch. Marquardt, G. Leuchs & U. L. Andersen, *Noise-powered probabilistic concentration of phase information*, Nature Physics **6**, 767–771 (2010)

M. A. Usuga, C. R. Müller, C. Wittmann, P. Marek, R. Filip, Ch. Marquardt, G. Leuchs & U. L. Andersen, "*Concentrating the phase of a coherent state by means of probabilistic amplification*", to appear in Proceedings of the 10th International Conference on Quantum Communication, Measurement and Computing (QCMC 2010), edited by T. Ralph and P. K. Lam (American Institute of Physics, Melville, NY, 2011)

**Conference presentations:**

C. R. Müller, M. Usuga, C. Wittmann, P. Marek, R. Filip, U. L. Andersen, Ch. Marquardt, and G. Leuchs, *Concentration of Phase Information*, DPG Frühjahrstagung March 8-12, 2010, Hannover, Germany

C. R. Müller, M. Usuga, C. Wittmann, P. Marek, R. Filip, Ch. Marquardt, U. L. Andersen, and G. Leuchs, *Concentration of Phase-Information*, CLEO/QELS, May 16-21, 2010, San Jose, USA

U. L. Andersen (invited), *Quantum protocols with coherent states of light*, QCMC 2010, July 19 – 23, 2010, Brisbane, Australia

R. Filip, *Quantum and semiclassical quantum noiseless amplifier*, The 17th Central European Workshop on Quantum Optics (CEWQO), June 6-11, 2010, St. Andrews, Scotland.

C. R. Müller, M. Usuga, C. Wittmann, P. Marek, R. Filip, Ch. Marquardt, U. L. Andersen, and G. Leuchs, *Noise-Powered Concentration of Phase Information*, ICONO/LAT, August 23-27, 2010, Kazan, Russia

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**Additional progress related to Deliverable 1.5:**
*Gaussian ameliorated measurement-induced disturbance*
(Partner USTAN, UP)

It has been known for some time that there exist some quantum information protocols for which the speed-up over classical protocols does not depend on quantum entanglement but relies instead on other non-classical correlations. In recent years this has sparked an interest in quantifying these correlations, most usually by defining measures as the difference between two classically equivalent expressions. The most famous of these are the quantum discord, the measurement-induced disturbance (MID) and the Ameliorated Measurement Induced Disturbance where a nontrivial optimisation problem is involved. We examined quantum correlations beyond entanglement in two mode Gaussian states. In analogy with recent studies of the Gaussian quantum discord, we defined a Gaussian Ameliorated Measurement Induced Disturbance (GAMID) by constraining the optimization to all bi-local Gaussian positive operator valued measurements. We were able to solve the optimization explicitly for relevant families of states, including squeezed thermal states. We also found that there is a finite subset of two-mode Gaussian states comprising pure states where non-Gaussian measurements disturb the state less than the most optimal Gaussian measurements - a counter-intuitive result. However for the majority of two mode Gaussian states the unoptimised MID provides a loose overestimation of the non-classical correlations present.

We derived formulae for calculating these quantities numerically, and where possible analytically. We then compared the different quantities on a sample of approximately 1 million randomly generated Gaussian states (see Fig. 1). Our findings provide a confirmation of the genuinely quantum nature of general Gaussian states, and yet reveal that non-Gaussian measurements can play a crucial role for the optimised extraction and potential exploitation of classical and non-classical correlations in Gaussian states.

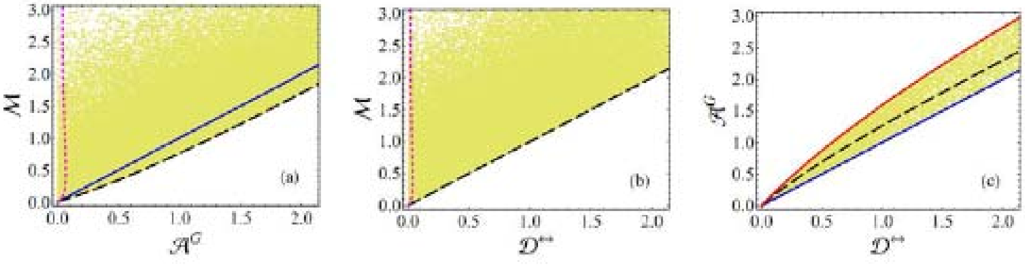

**Fig. 1.** *Comparison between (a) MID versus Gaussian AMID, (b) MID versus two-way Gaussian discord, and(c) Gaussian AMID versus two-way Gaussian discord, for* $10^5$ *randomly generated mixed two–mode Gaussian states. Pure two–mode squeezed states are accommodated on the dashed black curve in all the plots. See text for details of the other boundaries.*

**Publications:**

L. Mista, R. Tatham, D. Girolami, N. Korolkova and G. Adesso, Phys. Rev. A **83** 042325 (2011)

## Additional progress related to Deliverable 1.6:

*Continuous-variable quantum compressed sensing*
(Partner POTSDAM)

Detector process tomography has already been reported and D1.6 was delivered at month 24. Yet, some additional progress related more generally to quantum tomography has been achieved during the third reporting period. We have introduced a general theory of quantum compressed sensing which allows for the significantly more efficient and error-resilient quantum state tomography of continuous-variable systems. Technically, this is a theory of quantum compressed sensing based on tight frames. Physically, it is a readily usable recipe for efficiently reconstructing quantum states of optical modes based on homodyning or pointwise measurements of the Wigner functions with essentially the square root of the previously known effort, at full error control.

### Publications:

M. Ohliger, V. Nesme, D. Gross, and J. Eisert, in preparation (2011).

## Workpackage 2: Design of atomic components of CV quantum computing

Period covered: from 01/04/10 to 31/03/11
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 3 of the project

This workpackage is mainly devoted to preparation and manipulation of quantum states of atomic information carries, in particular atomic memories formed by ensembles of alkali metal atoms such as Cesium or Rubidium. During the second year of the project COMPAS, partner CNRS/ENS implemented atomic quantum memory based on electromagnetically induced transparency in hot Cesium vapor and demonstrated coherent storage and retrieval of faint coherent pulses of light. However, the efficiency of this memory was limited by the Doppler broadening. During the third year of the project, partner CNRS/ENS therefore developed and implemented effective cooling mechanism using additional laser de-pumping beams, which improved the induced transparency by a factor of 5. Partner CNRS/ENS also built another setup for memory that is based on cold Cs atoms held in a magneto-optical trap. This approach completely avoids the problems associated with room-temperature Doppler broadening. The resulting memory exhibits storage time of 1 μs and efficiency of 11%. It is anticipated that with shaped readout pulse and using dipole trap instead of MOT, these figures could be improved to 10 ms and 75%, respectively.

Partner NBI continued its experimental efforts aimed at preparing a highly non-classical non-Gaussian state such as Fock state in an atomic memory, which proved to be a formidable challenge. Several technical modifications have been suggested in order to avoid the technical noise that is very detrimental to this goal. These modifications include the replacement of the tramping laser or using strong magnetic bias field to be able to operate at the m=0 atomic clock transition. In parallel, an alternative experimental setup was constructed based on trapping cold atoms in the evanescent field of a tapered nanofiber, which should allow to achieve high optical densities of the sample and to work with smaller number of atoms, thereby reaching a regime where projection noise dominates over technical noise. Furthermore, an intriguing method for the preparation of various states of quantum memory via engineered dissipative light-matter interaction has been experimentally tested by partner NBI in collaboration with partner MPG. Using this method, EPR-type entanglement between two atomic memories has been generated and maintained for 0.04 s. Using continuous measurement on the output light then resulted in generation of steady state entanglement of atomic memories observed for up to an hour. Partner MPQ subsequently generalized this concept to a dissipation-driven quantum repeater.

Quantum memories are essential both for long-distance quantum communication and quantum computing. Partner ICFO proposed a new network geometry consisting of a line of quantum memories interacting with flying ancillary quantum particles that enables universal quantum computation. This hybrid scheme combines the advantages of both circuit and measurement-based quantum computing. An important application of quantum computer is an efficient simulation of the dynamics of complex physical systems. Partner POTSDAM in collaboration with the group of Prof. I. Bloch succeeded to experimentally demonstrate a strongly correlated 1D Bose gas in non-equilibrium. It was shown that, for short times, the system correctly simulates Bose-Hubbard dynamics while for large times, it proved impossible to classically simulate the dynamics of the system even using weeks of computing time on a supercomputer.

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

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

**Status:** Due month 36; Intermediate progress reported at month 12 and 24; Delivered.

**Partners:** NBI, MPG

Numerous results had already been reported during the first and second year in this direction. The final results completing the task are now reported by partners NBI and MPQ in the third year.

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### Progress towards Deliverable 2.1:

*Engineering and manipulating states in atomic quantum memory*
(Partner NBI)

This task aims at generating non-Gaussian states in an ensemble of cold atoms. A light beam interacts with a cold atomic ensemble of laser cooled atoms and becomes entangled with the atoms. A subsequent measurement of the light then projects the atoms into an entangled quantum state that is correlated with the measurement outcome.

In the first year of the project, we successfully used this technique to produce Gaussian entangled states that can be used to boost metrology applications beyond the projection noise limit and experimentally demonstrated the first neutral-atom clock beating this limit[1]. In the second year, we focused on creating non-Gaussian atomic states: A weak off-resonant excitation beam is used to drive a single atom from one long-lived hyperfine metastable state into another metastable state with a small success probability. The event will be heralded by a forward scattered photon with a frequency difference corresponding to the hyperfine splitting of 9 GHz [4].

The detection of this photon correlates with the excitation of a collective zero-transversal-momentum spin wave in the atomic ensemble. A following microwave $\pi/2^-$ pulse then should prepare a collective entangled state with a non-Gaussian population-difference between the two hyperfine states. Both the preparation and the detection of this population difference with a projection-noise resolving precision proved to be a formidable experimental challenge: For the detection the single photon has to be separated from the excitation pulse as well as from scattered photons caused by the few-Watt dipol-trapping laser. We constructed filters consisting of prisms, interference filters, polarizers and stabilized cavities that are able to separate light at the concerning frequencies.

In our clock experiment we used the $|F=3, m_F=0\rangle$ and $|F=4, m_F=0\rangle$ clock states as our states of interest. The high degree of symmetry of these states renders them higly insensitive to magnetic field fluctuations which makes them especially suitable for clock applications. The same symmetry, however, prevents us to drive a collinear 2-photon Raman-transition which is necessary to scatter the photon and to produce a zero-momentum spin-wave. We therefore experimentally investigated using the $|F=3, m_F=-1\rangle$ and $|F=4, m_F=+1\rangle$ sublevels, which also display a long coherence time. On the one hand these levels allow for an Λ-excitation scheme but on the other hand they require a 2-photon Microwave+radiofrequency pulse to perform the π/2 rotation. Unfortunately the high atom number and the correspondingly high atomic phase resolution of 0.18° (which was beneficial for the clock-application) prevented us to perform this rotation stably enough to resolve the atomic projection noise from technical noise sources in this more complicated scheme. Additionally intensity noise and mode instabilities of our ELS-Versadisk trapping laser affected the precise control of the experiment adversely.

We therefore proceeded in parallel on two tracks to reach our goal to produce non-Gaussian states:

- We replaced our trapping laser by a DBR-diode followed by a 10 W fiber amplifier. We developed a new excitation scheme using a strong magnetic field to break the rotational symmetry of the $|F=3, m_F=0\rangle$ and $|F=4, m_F=0\rangle$ clock states: A magnetic bias field rotates the emission lobe of the spontaneously scattered photon into the forward-direction during the excited-state lifetime. This allows us to re-use our proven methods for projection-noise limited measurements and state manipulation and detection [3, 1]. We currently are in the process of implementing this scheme. Unfortunately the advantages come at a price: Signal- and excitation photons have similar polarization, making their separation harder, and due to the high nuclear spin of Cesium the the efficiency of generating a Fock-excitation is intrinsically limited to 70% (although this latter limitation could be avoided by using $^{87}$Rb-atoms).
- In a collaboration with the group of A. Rauschenbeutel we prepared a tapered nanofiber and constructed a new vacuum setup. By trapping cold atoms in the evanescent field of a nanofiber high optical densities can be obtained with a smaller number of atoms [2]. The smaller number of atoms both carries the promise of the projection noise to dominate technical noise sources as well as a faster experimental cycle (see Fig. 1).

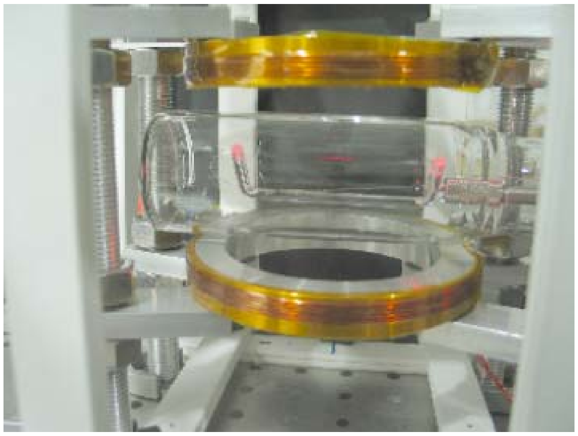

**Figure 1:** *New Nanofiber setup: A tapered nanofiber with a waist diameter of 500 nm is located in the center of a magneto-optical trap arrangement. Scattered light from a red laser illuminates the tapered section of the fiber.*

## References:

[1] A. Louchet-Chauvet, J. Appel, J. J. Renema, D. Oblak, N. Kjærgaard, and E. S. Polzik. *Entanglement-assisted atomic clock beyond the projection noise limit*, New J. Phys. 12, 065032 (2010)

[2] E. Vetsch, D. Reitz, G. Sagué, R. Schmidt, S. T. Dawkins, and A. Rauschenbeutel, *Optical Interface Created by Laser-Cooled Atoms Trapped in the Evanescent Field Surrounding an Optical Nanofiber*, Phys. Rev. Lett. 104, 203603 (2010).

[3] J. Appel, P. J. Windpassinger, D. Oblak, U. Busk Hoff, N. Kjærgaard, and E. S. Polzik. *Mesoscopic atomic entanglement for precision measurements beyond the standard quantum limit*, In: Proc. National Academy of Sciences 106, 10960 (2009)

[4] L. M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, *Long-distance quantum communication with atomic ensembles and linear optics*, Nature 414, 413 (2001).

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## Progress towards Deliverable 2.1:

*Entanglement between two atomic ensembles generated by dissipation*

(Partner MPG, NBI)

The light-matter interaction used for ensemble based quantum interfaces has been studied and the application of this type of interaction for dissipative entanglement generation has been analysed. Based on these results, two experiments have been realized, where dissipation induces entanglement between two macroscopic objects leading to robust and therefore long-lived entanglement. The generated entanglement is of EPR type (a two mode squeezed state) and plays a central role in continuous variable quantum information processing, quantum sensing and metrology. The system under investigation consists of two room temperature ensembles separated by 0.5m containing about $10^{12}$ atoms coupled to the environment composed of the vacuum modes of the electromagnetic field. In the first experiment, entanglement is generated by dissipation and maintained for 0.04s. In the second experiment, the dissipative mechanism is combined with continuous measurements and we demonstrate steady state entanglement observed for up to an hour.

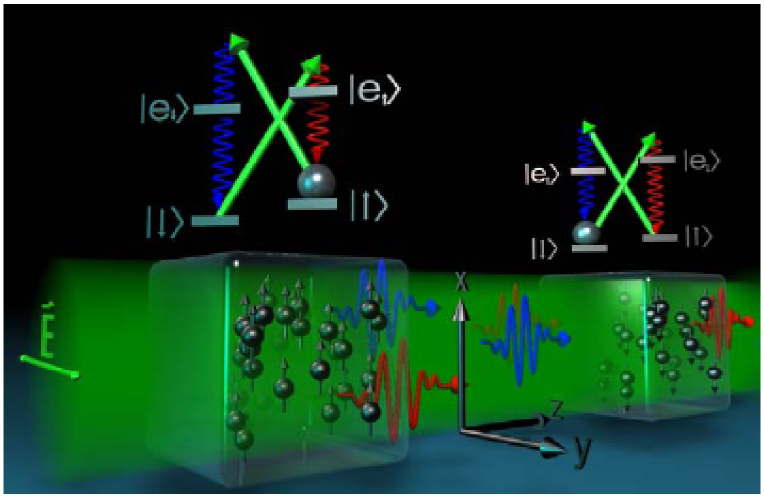

**Fig.1:** *Dissipative creation of entanglement between two atomic ensembles using light-matter interface techniques.*

**Publication:**

H. Krauter, C. A. Muschik, K. Jensen, W. Wasilewski, J. M. Petersen, J. I. Cirac, and E. S. Polzik , *Entanglement generated by dissipation*, arXiv:1006.4344 (2010).

Note that the theory paper related to this work has been reported in the EU project QUEVADIS while the experience is reported in the present project. Indeed, the theory was developed in QUEVADIS, which is a theoretical project on engineered dissipation, while the experimental implementation using mesoscopic atomic ensembles has been realized as part of COMPAS. This illustrated the synergy between the two projects.

**Conference presentations:**

- International Conference on Quantum Information and Computation 2010 in Stockholm, October 2010.
- Workshop “Hamiltonians and Gaps” in Cambridge, September 2010
- ESF research conference “Quantum engineering of States and Devices: Theory and Experiments“ in Obergurgl, June 2010
- CV-QIP workshop in Herrsching, June 2010
- ISPQT conference in Tokyo, April 2010

**Seminars:**

- Instituto Ciencia de Materiales in Madrid, February 2011
- Collège de France in Paris, February 2011
- University of Innsbruck, December 2010
- KIPT, University of California, Santa Barbara, November 2010
- ETH Zurich, October 2010
- Chalmers University of Technology, Gothenburg, September 2010
- University of Aarhus, April 2010

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

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

**Status:** Due month 24; Delivered month 24; Additional progress reported.

**Partners:** NBI, CNRS/ENS.

The task was completed at the end of the second year, but some additional experimental progress was anticipated. This is indeed the case, and some additional results on the quantum storage of light based on Cesium atoms trapped in a magneto-optical trap (MOT) are reported by CNRS/ENS. This quantum memory is expected to allow the storage of squeezed and entangled light pulses in a near future. Some general results on the universal light-matter interface is also reported by NBI and MPQ.

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### Additional progress related to Deliverable 2.2:

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

The quantum memory registers studied in this task rely on the transfer of quantum information from light to atoms (writing) and back from atoms to light (retrieval), using electromagnetically induced transparency (EIT) in atomic three-level transitions. The storage protocol involves a strong control field, generating EIT for the weak field that carries the quantum signal to be stored. The group velocity for the signal field is strongly reduced and the signal pulse is compressed by several orders of magnitude. A signal pulse can thus be contained inside the atomic medium, and before it propagates outside the medium, the control is switched off. The quantum variables of the signal field are then converted from a purely photonic state to a collective spin coherence. For read-out, the control field is turned on again. The medium emits a weak pulse, carrying the quantum information contained in the original pulse.

Two approaches have been carried out, the first one based on Caesium vapour, the second one on a cold Caesium cloud.

- ***Quantum storage in Caesium vapor***

We have shown in the previous periods that the process involving Caesium vapour allowed to store the two quadratures of a signal that is a faint coherent field in the atomic ensemble and then to retrieve them coherently. We have shown that the memory operates in the quantum regime. However the efficiency is rather low (~a few % in intensity). The storage efficiency decreases with the storage time, with a time constant ~10µs.

In order to improve the storage characteristics, we have performed a detailed theoretical and experimental study of EIT in Caesium vapour. As reported at month 24, we have shown theoretically that, when atoms have a hyperfine structure in the upper level, the EIT behavior is 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 (Doppler) broadening, the interplay between various velocity classes can be very detrimental to the transparency and thus to the memory efficiency [1, 2].

To restore the EIT in such cases, we have proposed an effective cooling mechanism through an engineered depopulation of some velocity classes that have been identified as detrimental. Using additional laser depumping beams, we have experimentally demonstrated significant changes in the EIT effect depending on the velocity distribution and we have improved the transparency by a factor of 5 [3]. This method opens new possibilities for the manipulation of EIT in alkali vapors. With an enhanced transparency of the atomic vapour, the efficiency of the atomic storage is expected to be significantly increased. Furthermore, beyond the specific medium used here, i.e. alkali-metal atoms at room temperature, our method, which allows an efficient engineering of the EIT properties of an inhomogeneously broadened medium, can be extended to various atom-like physical systems presenting simultaneously large broadening and multiple levels, e.g. in rare-earth doped crystals, quantum dots or NV-centers in diamonds.

- ***Light atom quantum interface in cold atomic ensembles***

Cold atomic ensembles offer several advantages for quantum storage, in particular lower decoherence, and consequently longer storage times. In addition, the EIT behaviour studied above is eliminated. In the second year, a new set-up using cold trapped Cesium was put together. In the present configuration, the atoms are trapped in a magneto-optical trap (MOT) and the magnetic field can be turned off in a very short time, in order for the atomic ensemble to be used as a storage medium in field-free environment.

The set-up (Fig.1) shows the arrangement of the optical systems for the quantum memory. The trapping laser beams used to create the MOT have not been represented. The control section shows the source of the control beam, which is a laser diode and its monitoring. The signal section allows to send a wide variety of signal beams including single mode and multimode coherent states or squeezed states. In the detection area, the MOT signal output is mixed with a local oscillator (LO) for homodyne detection. The beam displacers near the MOT allow to create two independent memory registers if needed. The photodiodes in the Optical Density section allow to measure the optical density, and also to carry out Raman spectroscopy.

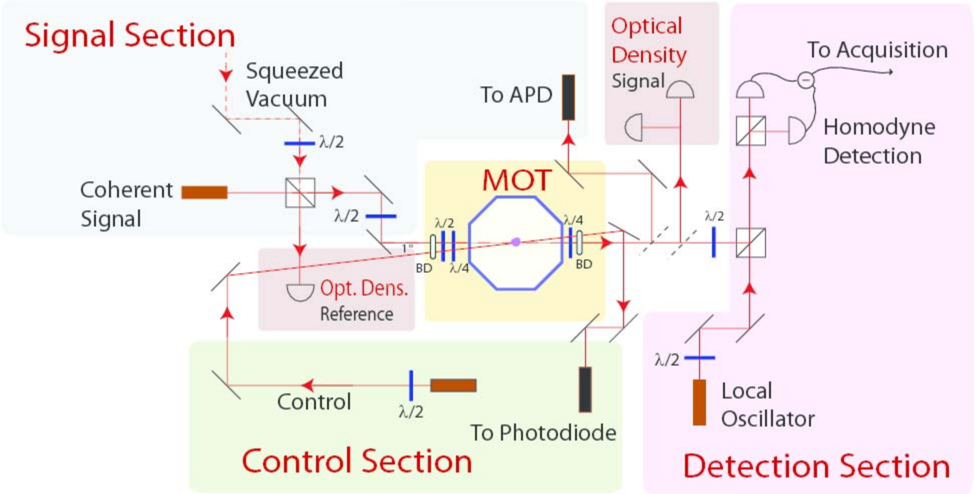

**Figure 1.** *Scheme of the experimental set-up*

The characteristics of the MOT have been carefully optimized to ensure high efficiency and long lifetime. In order to preserve atomic coherence and allow efficient storage, any inhomogeneous magnetic field should be suppressed. Cutting off the trapping magnetic field during storage is performed with a specific current driver circuit. A very small decay time of the MOT field, around 400µs has been demonstrated. After switching off the trapping field, the atomic ensemble is still subject to stray fields from the environment. These fields are suppressed with a set of compensation coils. Using a radiofrequency transition between the two ground states, the inhomogeneity of the magnetic field over the cold atomic ensemble has been decreased from a few 100 mGs to below 1mG.

An important property that determines the efficiency of storage is the optical density (OD) of the atomic ensemble. The OD is measured by sending a weak probe pulse into the atoms detuned from a resonant transition. The optical density in the MOT has been improved by using strong trapping beams with a large section area, generated by stabilized laser diodes. The OD that is currently obtained in the system is 35 in a cold atom cloud with a volume of 100 mm$^3$.

The memory characteristics have been first studied by storing a very faint pulse (around 0.1 mean photon number per pulse) on the 6S1/2, F=4 to 6P3/2 F=4 transition using a control beam on the 6S1/2, F=3 to 6P3/2 F=4 transition. The MOT is turned off during the memory phase. Results are presented in Fig.2 a and b. The presented recordings correspond to 1000 memory operations, with a signal pulse containing 1/10 photon on the average. For each operation the MOT light and magnetic fields are turned off, the pumping and control fields are turned on, then the signal pulse is sent and the control field is turned off and than turned on again after some delay, which is the storage time. In Fig.2a and b the black curve corresponds to the transmitted signal pulse in the absence of atoms; the red curves show two peaks. The first one is the detected field which “leaks” out of the atomic ensemble before the end of the control pulse and the second one is the retrieved signal pulse after read-out. In Fig. 2a, after 1 µs storage, the efficiency is 11%. In the absence of a signal pulse, no photons are detected during the read-out period. The memory lifetime is presently of the order of 10 µs.

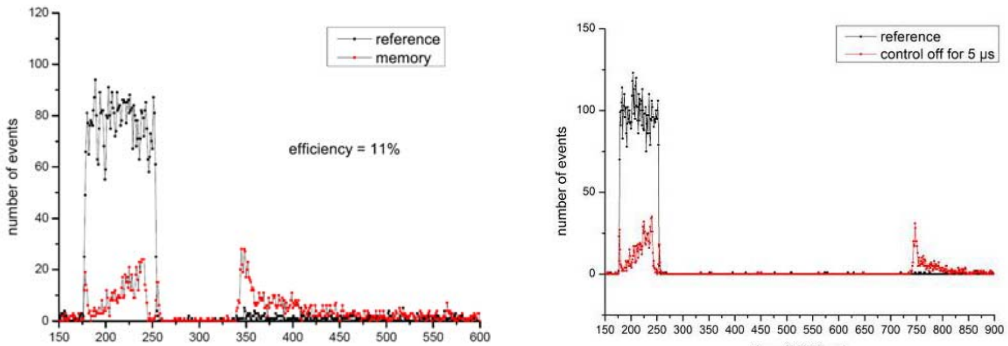

**Figure 2.** *Characteristics of the quantum memory*

In view of the parameters obtained in the present experimental set-up, the efficiency of the memory is expected to be improved to 35% for a square read-out pulse and can reach 75% with a shaped read-out pulse. The memory time will be eventually limited by the lifetime of the cold atomic ensemble, i.e. 100 µs. In further developments, the cold atoms will be trapped in a dipole trap. The memory time is then limited by the ground state coherence lifetime, which can reach 10 ms. Other schemes involving ultrashort pulses have been theoretically investigated for an optimized use of the memory [4]

These results demonstrate the quantum storage of a very faint light pulse with an efficiency comparable to the ones obtained in previous single photon storage experiments. With the observed characteristics this memory register is expected to allow the storage of squeezed and entangled light pulses.

**Publications :**

[1] Alexandra S. Sheremet, Leonid V. Gerasimov, Igor M. Sokolov, Dmitriy V. Kupriyanov, Oxana S. Mishina, Elisabeth Giacobino, Julien Laurat, *Quantum memory for light via a stimulated off-resonant Raman process: Beyond the three-level Λ-scheme approximation*, Phys. Rev. A **82**, 033838 (2010)

[2] O.S. Mishina, M. Scherman, P. Lombardi, J. Ortalo, D. Felinto, A.S. Sheremet, A. Bramati, D.V. Kupriyanov, J. Laurat, and E. Giacobino, *Electromagnetically induced transparency on an inhomogeneouly broadened Lambda-transition with multiple excited levels*, Phys. Rev. A **83**, 053809 (2011)

[3] M. Scherman, O.S. Mishina, P. Lombardi, E. Giacobino, and J. Laurat, *Enhancement of electromagnetically-induced transparency in a Doppler broadened medium*, arXiv 1106.0988 (quant-ph).

[4] T. Golubeva, Yu. Golubev, O. Mishina, A. Bramati, J. Laurat, E. Giacobino *High speed spatially multimode atomic memory*, Phys. Rev. A **83**, 053810 (2011)

**Popularizing science article :**

[1] *Mémoires quantiques : stocker l'insaisissable*, J. Laurat, Pour la Science, pp.102-110, Dossier trimestriel Juillet-Septembre 2010 (French version of scientific american)

**Conference contributions :**

*[1] Quantum Memories for information Networks,* E. Giacobino, Russian German French Laser Symposium 2011(Gossweinstain, Germany, April 2011) [INVITED TALK]

*[2] Quantum memory and repeater architecture with continuous variables,* J. Laurat, International conference on Quantum communication, measurement and computing QCMC2010 (Brisbane, Australia, July 2010) [INVITED TALK]

*[3] Quantum networking with continuous variables of atoms and light,* J. Laurat, 5th Asia-Pacific conference on quantum information science 5'APCQIS (Taiyuan, China, august 2010) [INVITED TALK]

## Additional progress related to Deliverable 2.2:

*Universal light-atoms quantum interface for quantum information processing*
(Partner MPQ, NBI)

We have reviewed the recent research towards a universal light-matter interface. Such an interface is an important prerequisite for long distance quantum communication, entanglement assisted sensing and measurement, as well as for scalable photonic quantum computation. The developments in light-matter interfaces based on room temperature atomic vapors interacting with propagating pulses via the Faraday effect are reviewed. This interaction has long been used as a tool for quantum nondemolition detections of atomic spins via light. It was discovered recently that this type of light-matter interaction can actually be tuned to realize more general dynamics, enabling better performance of the light-matter interface as well as rendering tasks possible, which were before thought to be impractical. This includes the realization of improved entanglement assisted and backaction evading magnetometry approaching the Quantum Cramer-Rao limit,quantum memory for squeezed states of light and the dissipative generation of entanglement. Moreover, a possible interface between collective atomic spins with nano- or micromechanical oscillators is reviewed, providing a link between atomic and solid state physics approaches towards quantum information processing.

### Publication:

C. A. Muschik, H. Krauter, K. Hammerer, and E. S. Polzik, *Quantum information at the interface of light with mesoscopic objects*, arXiv:1105.2957 (2011). Contribution to the Quantum Information Processing special issue on neutral particles edited by R. Folman

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

**Deliverable2.3:** ***Interfacing light with atoms in optical lattices and trapped ions***
**Status:** Due month 24; Delivered on time; Additional results reported.

**Deliverable2.4:** ***Alternative methods for generating non-Gaussian states using Kerr nonlinearity***
**Status:** Due month 24; Delivered on time; Additional results reported.

**Partners:** MPG, USTAN, CNRS/IO

Although this task was completed at month 24, some additional have been obtained from the exploration of novel effects to get high nonlinear refractive index for quantum gates. In particular, Partner MPQ investigated large quantum superpositions of nano-dielectrical objects as a candidate system for the Kerr interaction, which is reported as additional progress towards D2.4. Concerning D2.3, partner MPQ reports on some new approach for the realization of a quantum interface between single photons and single ions in an ion crystal, while partner POTSDAM studies *isolated strongly correlated 1D Bose gas* a candidate CV quantum simulator.

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### Additional progress related to Deliverable 2.3

*Interfacing light with single ions in an ion crystal*
(Partner MPQ)

A new approach for the realization of a quantum interface between single photons and single ions in an ion crystal has been proposed and analyzed in detail and applications including the generation of single photons, memories for quantum repeaters, and deterministic photon-photon, photon-phonon, or photon-ion entangling schemes have been discussed.

In this new approach, the coupling between a single photons and a single ion is enhanced via the collective degrees of freedom of the ion crystal. The scheme can be implemented in several possible ion trap setups such as $^{40}Ca^+$ or $^{88}Sr^+$ trapped ions and may be used for the realization of deterministic quantum gates between distant trapped ions.

**Publications:**

L. Lamata, D. R. Leibrand, I. L. Chuang, J. I. Cirac, M. D. Lukin, V. Vuletic, and S. F. Yelin, *Ion crystal transducer for strong coupling between single ions and single photons*, arXiv:1102.4141 (2011).

**Conference presentations:**

- American Physical Society March Meeting 2011 in Dallas, March 2011.

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### Additional progress related to Deliverable 2.3

*Probing the relaxation towards equilibrium in an isolated strongly correlated 1D Bose gas*
(Partner POTSDAM)

We were able to experimentally demonstrate and theoretically discuss the first observation of strongly correlated quantum many-body systems in non-equilibrium. The system is in its essence a multi-mode continuous-variable system. It also constitutes a first quantum simulator outperforming the best known classical algorithm to date, in that the controlled system dynamics in the lab can be certified for short times to be correctly simulate Bose-Hubbard dynamics, while for large times the best known algorithms cannot keep track of the dynamics, even using weeks of computing time on supercomputers in Juelich [1].

**Publications:**

[1]. S. Trotzky, Y.A. Chen, A. Flesch, I.P. McCulloch, U. Schollwoeck, J. Eisert, and I. Bloch, arXiv:1101.2659, submitted to *Nature Physics* (2011).

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## Additional progress related to Deliverable 2.4

*Large quantum superpositions of nano-dielectrical objects as a candidate system for the Kerr interaction*

(Partner MPQ)

A general quantum theory for using an optically levitating nanodielectric as cavity optomechanical system has been developed. Based on these results, a light-mechanics interface is designed which allows for the preparation of non-Gaussian states such as quantum superpositions of Fock states. The non-Gaussian light-mechanics interface can be interpreted as an effective means to obtain non-linear effects in optomechanical systems. Moreover, a scheme to perform direct full tomography of the mechanical state is introduced, see Fig. 1.

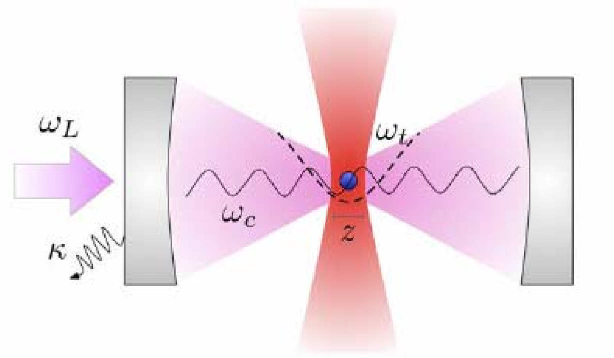

**Fig.1:** *Illustration of the setup: a nanodielectric is placed inside an optical cavity and confined by optical tweezers.*

**Publications:**

O. Romero-Isart, A. C. Pflanzer, F. Blaser, R. Kaltenbaek, N. Kiesel, M. Aspelmeyer, and J. I. Cirac, *Large Quantum Superpositions and Interference of Massive Nano-objects*, arXiv:1103.4081 (2011).

O. Romero-Isart, A. C. Pflanzer, M. L. Juan, R. Quidant, N. Kiesel, M. Aspelmeyer, and J. I. Cirac, *Optically Levitating Dielectrics in the Quantum Regime: Theory and Protocols*, Phys. Rev. A **83**, 013803 (2011).

## Conference presentations:

- Workshop on Optomechanics and Macroscopic Cooling at ITAMP (Harvard University), February 2011.
- International Conference on Quantum Information and Quantum Computation in Stockholm, October 2010.
- 5th International Workshop DICE2010 in Castiglioncello, September 2010.
- Workshop on Nano-Opto-Electro-Mechanical Systems Approaching the Quantum Regime in Trieste, September 2010.
- XXXIV International Conference of Theoretical Physics: Correlations and Coherence at Different Scales in Ustron, September 2010.
- XIII International Conference on Quantum Optics and Quantum Information in Kyiv, May 2010.
- 17th Central European Workshop on Quantum Optics in St. Andrews, June 2010.
- Annual Meeting of the Alexander von Humboldt Foundation in Berlin, June 2010.
- ISPQT conference in Tokyo, April 2010

## <u>Task 2.4</u>: Developing quantum networks based on CV quantum repeaters

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

**Status:** Due month 24; Delivered; Additional progress reported.

**Partners:** NBI, MPG, DTU

Although this task had been completed at month 24, some new quantum network architectures that may be useful in a quantum repeater have been found by partners MPQ and ICFO, which are reported on for the third year of the project.

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### Additional progress related to Deliverable 2.5:

*Dissipative quantum repeater architecture*
(Partner: MPQ)

Even though entanglement is very vulnerable to interactions with the environment, it can be created by purely dissipative processes. Yet, the attainable degree of entanglement is profoundly limited in the presence of noise sources. We have shown that distillation can also be realized dissipatively, such that a highly entangled steady state is obtained.

In this work, several methods for accomplishing the task of distilling steady state entanglement are put forward and analyzed. One of these is based on a variant of the dissipative entangling process which has been used for the generation of entanglement between two atomic ensembles (arXiv:1006.4344). The ability to distill entangled states is an important prerequisite for repeater schemes. We have shown how dissipative distillation can be employed in a continuous quantum repeater architecture in order to produce long-range high-quality entangled steady states. The required resources scale only polynomially with the distance, see Fig. 1.

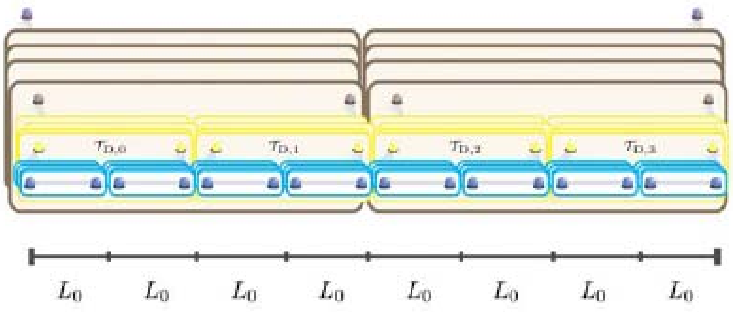

**Fig.1:** *Dissipative quantum repeater architecture. Each basic link of length $L_0$ dissipatively driven into an entangled steady state. A steady-state entanged link can be for example established using a variant of the light-matter interface based scheme introduced above (arXiv:1006.4344).*

### Publication:

K. G. H. Vollbrecht, C. A. Muschik, and J. I. Cirac, *Entanglement distillation by dissipation and continuous quantum repeaters*, arXiv: 1011.4115 (2011).

**Conference presentations:**

- International Conference on Quantum Information and Computation 2010 in Stockholm, October 2010.

**Seminars:**

- Instituto Ciencia de Materiales in Madrid, February 2011
- Collège de France in Paris, February 2011
- KIPT, University of California, Santa Barbara, November 2010

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**Additional progress related to Deliverable 2.5:**
*Sequential measurement-based quantum computing with memories*
(Partner: ICFO)

Here, we report on a new network geometry, consisting of a line of interacting memories (e.g., ensemble memories) interacting via flying quantum particles (e.g., atoms or light), that enables quantum computation.

There are two main approaches for quantum computation: the circuit model and measurement based quantum computation. From a theoretical point of view, the two models are equivalent. However they offer complementary advantages when considering quantum computation implementations. Historically, the first model for quantum computation was the circuit model. In this approach, all gates are decomposed into one-body (local) and two-body (entangling) unitary operations, and the output is read out by measuring the system's final state. A major advantage of the circuit model is that it requires the generation and coherent preservation of many-body entanglement only on a number of system constituents linear with the logical inputs. On the other hand, the sequence of operations must be adapted to each given computation, which represents a considerable obstacle from an experimental viewpoint. In particular, entangling operations must be actively applied on-line during the course of the computation while simultaneously preserving the system's quantum coherences.

In contrast, in the measurement based quantum computation model, proposed later by Raussendorf and Briegel, the computation is performed by adaptive local measurements on certain quantum lattices in universal many-body-entangled resource states. The clear advantage is that no demanding on-line operations are required throughout the computation: only measurement bases must be (locally) adapted, whereas the generation of the resource state is independent of the given computation. The price to pay, however, is that universality is attained only with two-dimensional lattices, implying that the number of system components typically scales quadratically with the logical inputs. To make things worse, such many-body entangled states seem not to be trivial to find in natural systems. All in all, and despite the success in singling them out as ground states of specific, relatively simple Hamiltonians, their generation or coherent preservation still remain a challenge.

In this task, we have introduced a hybrid model of quantum computation that combines the main practical advantages of the circuit and measurement-based quantum computation models. The procedure is completely general and can be applied both to discrete-variable systems of any dimension and continuous variables. Our proposal consists of an array of static, long-lived quantum registers - quantum memories - that sequentially interact with moving, short-lived quantum registers - the flying registers - via a fixed interaction (the only entangling operation required), see Fig. 1. The architecture of the system operations stays the same throughout and only the measurement bases must be adapted at each step, preserving the main advantages of the measurement based approach. However, in contrast to the latter, here quantum information does not flow from a physical site to another but in each step is stored in the memories. These are the only quantum systems required to possess full coherence robustness along the computation. Thus, a number of memories equal to the logical inputs suffices for universal computation.

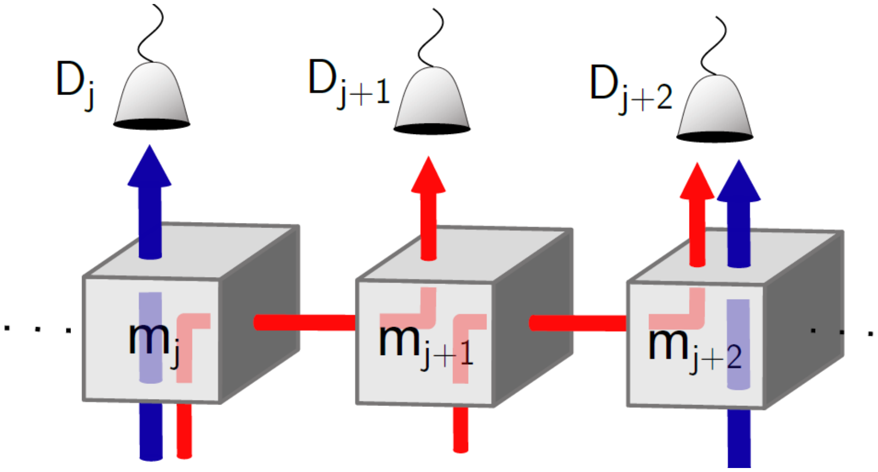

**Figure 1:** *Pictorial sketch of our sequential model for quantum computing: long-lived quantum systems, quantum memories, iteratively interact at fixed interfaces with moving registers, flying registers. Registers do not need to be temporally synchronized and can also mediate the interaction between memories (thin curves).*

For the case of two-dimensional systems, our formalism recovers the ancilla-driven model. This model, originally derived within a different framework, already has most of the implementation virtues described above. The main advantage here is that our derivation enables the direct application of topological fault-tolerant techniques already developed for standard measurement based models to our approach. For the continuous-variable case, in turn, our formalism recovers some aspects of recent experimental proposals. Nevertheless, our model does not require pulse synchronization, long fiber loops, and non-linear photon-photon interactions, which were needed in the previous proposals. Our approach, then, alleviates these experimental requirements and can be realized using experimentally accessible quantum interfaces.

**Publication:**

Augusto J. Roncaglia, Leandro Aolita, Alessandro Ferraro, Antonio Acin , *Sequential measurement-based quantum computing with memories*, accepted for publication in Phys. Rev. A.

## Workpackage 3: Demonstration of mesoscopic CV quantum processors

Period covered: from 01/04/10 to 31/03/11
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 3 of the project

This workpackage is primarily devoted to demonstrating mesoscopic CV quantum processor, in particular quantum gates on CV carriers of quantum information. In this context, cat-state quantum computing, where the qubits are encoded into superpositions of two coherent states, emerges as a particularly promising candidate for proof-of-principle experimental tests. Partner UP proposed simplified experimentally feasible schemes for the implementation of single- and two-qubit quantum gates with cat states. The driving force of all these gates is a single-photon subtraction that is now well mastered by several COMPAS experimental partners, so that this theoretical proposal was very soon followed by two experimental demonstrations by partners CNRS and DTU. Partner CNRS implemented the elementary sign-flip operation that transforms an even cat to an odd cat and vice versa. Remarkably, this manipulation can be conditionally accomplished simply by subtracting a single photon from the state. Partner CNRS performed a detailed characterization of this operation based on the various relevant experimentally determined parameters. It was found that the experimentally observed gate exhibits a high quantum process fidelity of 0.78.

An intriguing aspect of cat-state quantum computing is that the most demanding gate is not the two-qubit entangling gate but rather the single-qubit Hadamard gate, which transforms coherent states onto their superpositions (odd or even cat states). Partner DTU therefore decided to experimentally implement this challenging gate following the theoretical proposal by partner UP. The gate requires an ancilla even cat-like state that was approximated in the experiment by a squeezed vacuum state (fidelity more than 90% with the ideal cat state). The core of the gate again consists of a single photon subtraction but in addition it is combined with coherent displacement of the input state and conditioning on outcome of a homodyne measurement on one of the output modes. The resulting Hadamard gate achieves fidelity 94% for input coherent state $|\alpha>$ and output even cat, and 51% for input $|-\alpha>$ and output odd cat.

Besides quantum gates and quantum computers, another important example of a quantum processor is a quantum repeater, whose core part consists of entanglement distillation. Building upon the results achieved in previous years of project COMPAS, partner UP continued the investigation of advanced entanglement distillation protocols for CV entangled states. A nested distillation protocol for Gaussian states was proposed that simultaneously distills entanglement and purifies the states (it asymptotically converges to pure entangled two-mode squeezed vacuum). A key feature of the scheme is a two-copy de-Gaussification procedure that involves approximate noiseless quantum amplifiers with negative gain as non-Gaussian quantum filters. This is yet another example of exploiting the tools developed in WP1 for more complex tasks studied within WP3. Partner UP together with prof. R. Schnabel at Hannover also demonstrated first collective three-copy Gaussification and entanglement distillation of two-mode CV entangled states represented by de-phased two-mode squeezed vacua. In a related work, partner POTSDAM showed that several types of Gaussification protocols can be seen as special instances of a more general mother protocol. At the basis of the argument, a new type of non-commutative central limit theorem is at work. In this way, the previously known schemes leading to Gaussian states could be unified.

## 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; Delivered.

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

**Partners:** DTU, FAU, CNRS/IO

During the third year of the project, partner UP has proposed a general scheme in order to implement quantum gates with cat-state qubits. This has been very soon followed by two experimental demonstrations of this scheme: partner CNRS/IO has experimentally implemented the coherent-state sign-flip operation, leading to D3.1, while partner DTU has carried out the experimental demonstration of a Hadamard gate for coherent-state qubits, leading to D3.2.

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### Reported progress towards Deliverable 3.1:

*Cat-states implementation of quantum gates*
(Partner UP)

Partner UP proposed an alternative way of implementing several elementary quantum gates for qubits in the coherent state basis – the cat state qutbits $c_0|\alpha>+c_1|-\alpha>$. The operations are probabilistic and employ single-photon subtractions as the driving force. The single qubit PHASE gate is illustrated in Fig. 1. The schemes for single-qubit PHASE gate and two-qubit controlled PHASE gate are capable of achieving arbitrarily large phase shifts with currently available resources, which makes them suitable for near future experimental demonstrations.

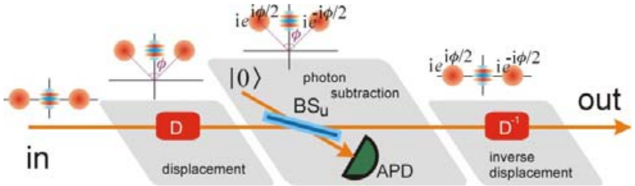

**Fig. 1.** *Scheme for feasible demonstration of single-qubit phase gate for cat-states. D – displacement, $BS_u$ – unbalanced beam splitter, APD – avalanche photo-diode*

Instead of focusing on gates for a specific class of CV quantum states (such as cat states), one can try to approach quantum computation by using general operations which can by applied to an arbitrary CV quantum state. Of these operations, those with Hamiltonians linear or quadratic in quadrature operators (displacement and squeezing) are readily available in contemporary experimental practice. However, operations with Hamiltonians at least cubic in quadrature operators are, as of yet, unattainable. Partner UP proposed a feasible way of deterministically implementing weak quantum nonlinear operation with cubic Hamiltonian $H=gx^3$. The experimental setup is sketched in Fig.2. A non-classical state is specifically engineered by a proper sequence of photon subtractions, and the nonlinearity is subsequently imprinted on the target state by means of Gaussian operations, homodyne measurement and feed-forward.

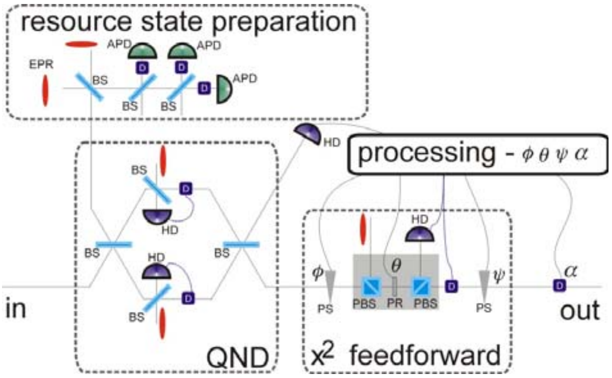

**Fig. 2.** *Scheme for deterministic implementation of* $x^3$ *operation. BS – beam splitter, APD – avalanche photo diode, HD – homodyne detection, D – displacement, EPR – two mode squeezed state, PS – phase shift, PBS – polarization beam splitter, PR – polarization rotator*

**Publications:**

P. Marek, J. Fiurášek, *Elementary gates for quantum information with superposed coherent states*, Phys. Rev. A 82, 014304 (2010).

P. Marek, R. Filip, A. Furusawa, *Deterministic implementation of teak quantum cubic nonlinearity*, in preparation

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**Reported progress towards Deliverable 3.1:**
*Cat-states implementation of the sign-flip operation*
(Partner CNRS/IO)

A first basic operation to be implemented for CV cat-states computing is the sign-flip operation, that can transform an odd photon-number Schrödinger cat to an even one, and conversely. We experimentally implemented this quantum gate following a non-deterministic protocol proposed by partner UP in this task [1]. The operating principle relies on an application of the photon subtraction operator, which can be approximated by a sampling beamsplitter of low reflectivity followed by a detection event on a photon counter. There have been demonstrations of such an effect, but so far the characterization has focused on the states that could be produced by this technique, rather than on the device itself.

Due to decoherence processes, gates in a coherent states architecture most likely will not leave the output state inside the original reduced Hilbert space spanned by coherent states qubits $|\alpha\rangle$ and $|-\alpha\rangle$. Moreover, the current technologies do not even warrant that input test states belong to this space. Therefore, we cannot simply use standard techniques, such as process tomography, for a characterization. We proposed a way for characterizing these gates, which does not rely on a black-box approach, but requires some modelling of the functioning of the gate. One can identify a small number of parameters, accessible to the experimentalist, by which the gate process can be modelled (in the present case we have: the amplitude $\alpha$ of the coherent states, the transmission T of the sampling beamsplitter, and the modal purity $\xi$). The behaviour of the device can then be obtained for ideal inputs.

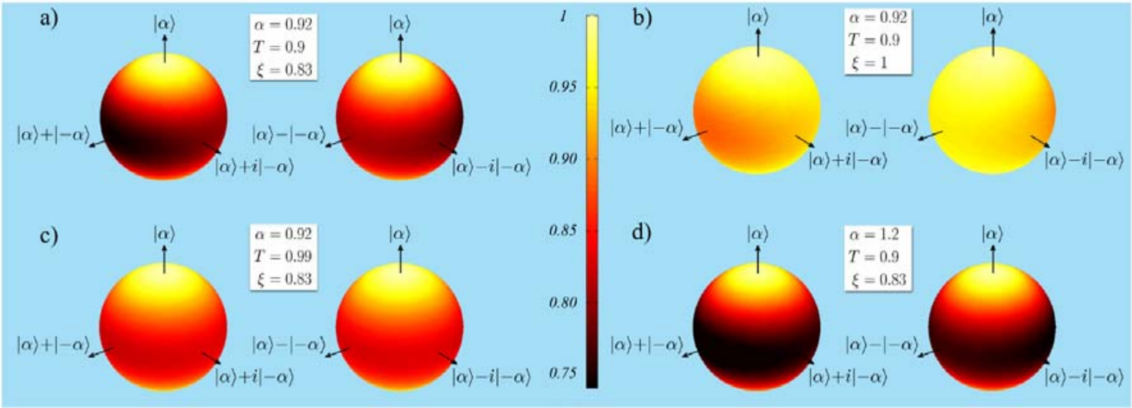

**Figure 1:** *Fidelities of the output states for arbitrary ideal inputs* $\cos(\theta/2)\left|\alpha\right\rangle + e^{i\varphi}\sin(\theta/2)\left|-\alpha\right\rangle$ *represented on the Bloch sphere a) for our phase gate; b) for a perfect modal purity* $\xi = 1$*; c) for a device with* $T = 0{:}99$*; d) for our device with* $\alpha = 1.2$*.*

The figure above provides us with extensive information about our device, but fail in delivering us a conclusive answer on how good is the gate overall. In order to derive a more global characterization, we retained the underlying physical idea behind Jamiolkowski's isomorphism [2]: Since we are interested in the overall behavior of the gate, we need to estimate its action on all the inputs at the same time: this amounts to feed in the gate half of an entangled pair. In light of these considerations, we can adopt as a reasonable figure of merit a fidelity between entangled states. We find F=0.78 for the experimentally observed gate (red dot on the figure below).

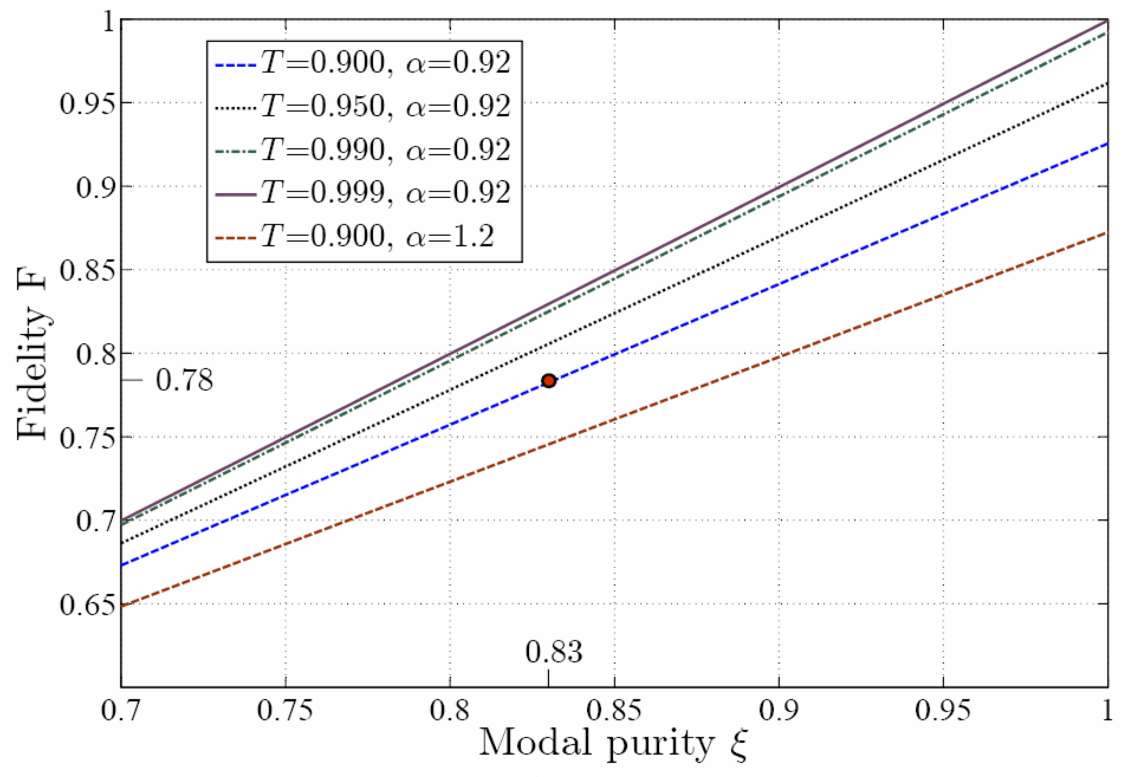

**Figure 2:** *Fidelity of an entangled output from the phase gate with the ideal entangled state. The red dot corresponds to our experimental parameters.*

**References:**

[1] P. Marek, and J. Fiurášek, Phys. Rev. A 82, 014304 (2010).
[2] A. Jamiolkowski, Rep. Math. Phys. 3, 275 (1972).

**Publications:**

R. Blandino, F. Ferreyrol, M. Barbieri, P. Grangier and R. Tualle-Brouri, *A method for characterizing coherent-states quantum gates*, arXiv:1105.5510 (2011), submitted to New Journal of Physics.

**Conference presentations:**

P. Grangier, "Information processing with continuous variables", CV-QIP'10: 7th Workshop on Continuous-Variable Quantum Information Processing, Herrsching, Allemagne, 11-14 juin 2010 (2010).

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**Reported progress towards Deliverable 3.2:**
*Experimental demonstration of a Hadamard gate for coherent-state qubits*
(Partner DTU)

In the standard linear quantum computing protocol of Knill, Laflamme and Milburn, energy eigenstates (such as the polarization degree of freedom of a single photon) serve as the computational basis. As an alternative it is possible to use non-orthogonal mesoscopic coherent states, $|\alpha>$ and $|-\alpha>$, as the computational basis. Although these states are non-orthogonal, resource efficient and fault tolerant quantum gates can be implemented with these states.

Such an approach was put forward by Ralph et al using either a rather complex deterministic scheme (Phys. Rev. A 68, 42319 (2003)) or a much simpler probabilistic scheme (Phys.Rev. Lett. 100, 030503 (2008)). An even simpler implementation of a universal set of non-deterministic quantum gates was recently suggested by partner UP in this Task. They proposed the physical realization of a single mode and a two-mode phase gate as well as the Hadamard gate.

In this work we have experimentally implemented the Hadamard transform of coherent states as suggested by Partner UP. The protocol is simply based on a squeezed state resource, linear operations and two projective measurements; a discrete variable and a continuous variable measurement. By injecting the computational basis states ($|\alpha>$ and $|-\alpha>$) into the gate we characterize its function by reconstructing the Wigner functions of the transformed output states and calculate the fidelity with ideally transformed state.

A schematic of the Hadamard gate is presented in Fig. 1. The input state – a coherent state superposition – is first displaced by an amount equal to the excitation of the coherent states of the computational basis. A single photon is then jointly subtracted from the displaced input state and a resource state (a coherent state superposition state) by means of beam splitters and a single photon counter. Finally, the state is projected onto an amplitude quadrature using a homodyne detector, and the remaining mode falls into the Hadamard transformed state.

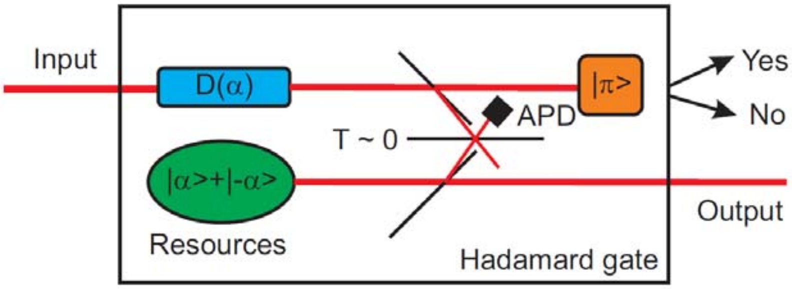

***Fig. 1***. *Schematic of the Hadamard gate. In the experimental realization, the resource state was replaced by a squeezed state and the |π> projector was a homodyne detector; if the quadrature measurement outcome fall within a certain interval and the APD is firing, the output is projected onto a Hadamard transformed state.*

We implement the gate using a squeezed state as a resource in replacement of the coherent state superposition state as the overlap between these two states was more than 90%. The squeezed state is produced through down-conversion in a periodically poled KTP crystal pumped with pico-second pulses at 415nm, thus producing pulsed squeezed light at 830nm. As an input state we use either |α> or |-α> which are displaced to |0> and |2α>. To simplify the scheme, the input state is defined in the same spatial mode as the ancillae squeezed state but in orthogonal polarization modes; this facilitate the mixing of the two modes in a waveplate followed by a polarizing beam splitter. By jointly subtracting a single photon from the two states using an APD and by conditioning the output on successful quadrature measurement outcomes, the final state is formed and fully characterized by means of homodyne tomography.

The results of a Hadamard transform of the two inputs, |α> and |-α>, are shown in Fig. 2 and 3. We present the density matrices and the Wigner functions of the two outputs, and compute the fidelities to the ideally transformed states.

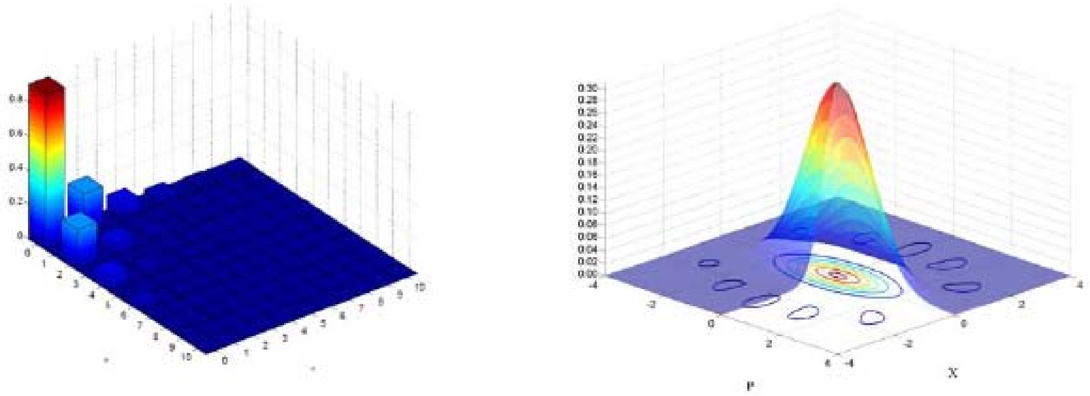

***Fig. 2***. *Density matrix and Wigner function for the output state for |a> as the input state. The Fidelity to the ideal output state is F=94%.*

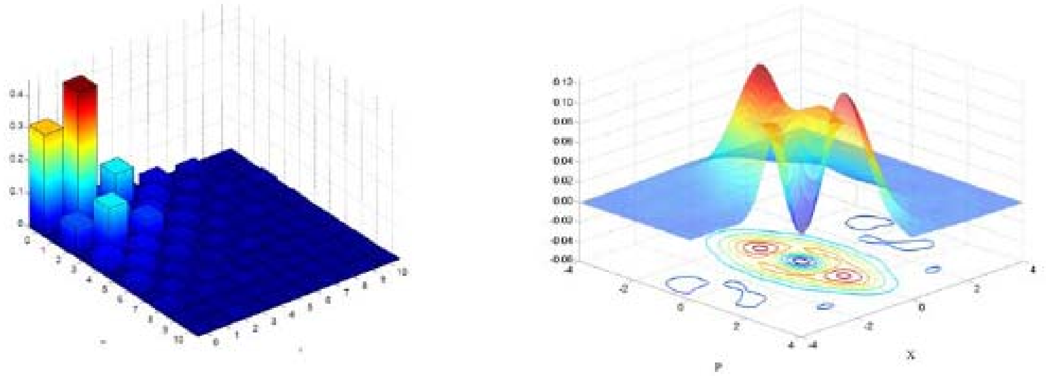

***Fig. 3**. Density matrix and Wigner function for the output state for |-a> as the input state. The fidelity to the ideal output state is F=51%.*

Due to different imperfections of the gate, the fidelity is not unity and furthermore, the fidelity is state dependent. We have seen that by injecting, |α> and |-α>, the fidelity varies from 51% to 94%. Based on the carefully studied experimental parameters, we find the expected fidelities for all coherent state superposition states on the Bloch's sphere. These fidelities are illustrated as contours on the sphere in Fig. 4. In order to increase the fidelities and make them more homogeneous, the resource state must be replaced by a pure coherent state superposition state.

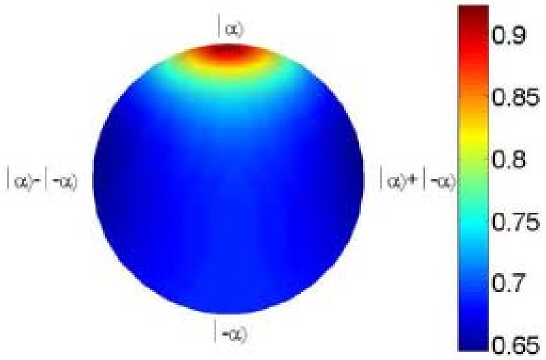

***Fig. 4**. Fidelities of the Hadamard transform visualized on the Bloch's sphere for coherent state superposition states.*

**Presentations:**

*Experimental demonstration of a Hadamard Gate for Coherent State Qubits*, Anders Tipsmark, Ruifang Dong, Amine Laghout, Miroslav Jezek and Ulrik L. Andersen, CLEO, The Conference on Lasers and Electro-Optics, Munich, Germany, 22-27 May (2011). Contributed talk.

*Continuous Variable Quantum Communication and Computation*, Ulrik L. Andersen, Anders Tipsmark, Ruifang Dong, Amine Laghout, Miroslav Jezek CLEO, The Conference on Lasers and Electro-Optics, Baltimore convention center, Baltimore, Maryland, USA, 1-6 May 2011. INVITED TALK.

*Quantum Information Processing with Discrete and Continuous Variables*, Ulrik L. Andersen, Anders Tipsmark, Ruifang Dong, Amine Laghout, Miroslav Jezek, International Conference on Quantum Information (ICQI), June 6-8 2011, Uni. of Ottawa, Canada. INVITED TALK.

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

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

**Status:** Due month 24; Intermediate progress at month 12; Delivered on time.

**Partners:** DTU, FAU, ULB, and UP

The first CV quantum erasure-correcting code, which protects coherent states of light against complete erasure, has been proposed by partner ULB and experimentally demonstrated by partners FAU and DTU during the first and second years of the project, leading to D3.3 at month 24. There was no further work on this task during the third year of the project.

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

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

**Status:** Due month 24; Delivered at month 12; Additional progress reported at month 24.

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

There were numerous contributions to this task reported during the first year (at the end of which the goal was attained already) as well as during the second year (at the end of which some additional progress was reported). There was no further work on this task during the third year of the project.

## **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

Although this task had been completed in advance, additional progresses have been achieved during year 2 and year 3. The progress achieved by partners UP, USTAN, POTSDAM and ULB during year 3 is reported here.

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### **Additional progress related to Deliverable 3.5:**

*Advanced distillation and purification of entangled Gaussian states*
(Partners UP)

Iterative CV entanglement distillation protocols for Gaussian states typically combine two steps. First, Gaussian states are de-Gaussified by appropriate local quantum filters in order to by-pass the no-go theorem on distillation of Gaussian entanglement by Gaussian operations. Second, the states are re-Gaussified by an iterative procedure whose each step involves interference of two copies of a two-mode state on balanced beam splitters, followed by projection of one output on each side on a vacuum. This protocol converges to a Gaussian state which may be highly entangled. However, it will generally be mixed for the non-Gaussian quantum filters considered so far in the literature.

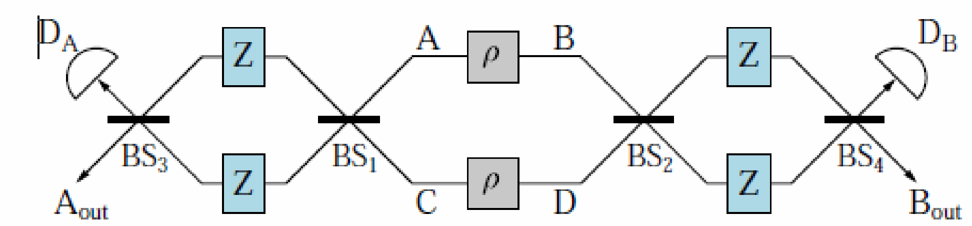

**Fig. 1:** *Two-copy de-Gaussification scheme. $BS_j$ denotes balanced beam splitter, Z indicates a non-Gaussian operation – a Fock state filter $Z = n - 1$ that removes the single-photon term, and each detection block $D_j$ makes projection onto a superposition of vacuum and single photon state.*

Partner UP therefore theoretically developed an entanglement distillation and purification scheme for Gaussian states that asymptotically converges to a *pure* entangled Gaussian state for any input mixed entangled symmetric Gaussian state. A key feature of the suggested protocol is that it utilizes a two-copy de-Gaussification procedure that involves a Mach-Zehnder interferometer with single-mode non-Gaussian filters $Z=n-1$ inserted in its two arms, see Fig. 1. The required non-Gaussian filtering operations can be implemented by coherently combining two sequences of single-photon addition and subtraction operations similarly as the recently demonstrated noiseless quantum amplifier. The whole protocol including de-Gaussification and Gaussification should be repeated several times. Figure 2 shows the purity and entanglement of formation of Gaussian state obtained after N stages of such nested distillation protocol. The initial state is a two-mode squeezed vacuum transmitted over a lossy channel with transmittance T.

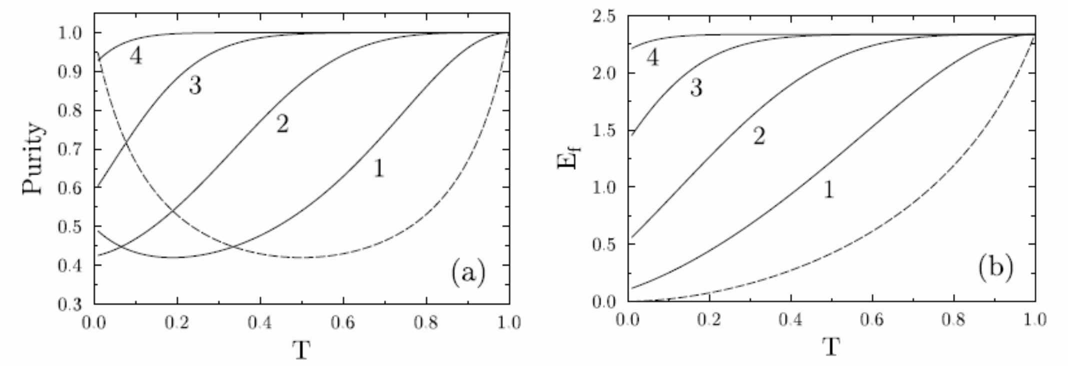

**Fig. 2:** *Purity (a) and entanglement of formation (b) of distilled Gaussian state after N stages of nested entanglement distillation protocol is plotted as a function of the effective channel transmittance T for a fixed effective two-mode squeezing constant r = 1. The numerical labels indicate number of stages N of the protocol, dashed lines represent values of P and $E_f$ for the initial state before distillation.*

An essential part of the entanglement distillation scheme is the iterative Gaussification protocol. Partner UP together with group of prof. Roman Schanbel at Albert Einstein Institute, Hannover, therefore focused on this procedure and experimentally demonstrated the first collective three-copy Gaussification protocol. Non-Gaussian states obtained by transmitting the entangled two-mode squeezed vacua through de-phasing channels were used as test states in the protocol. Note that entanglement of such non-Gaussian states can be distilled by this protocol.

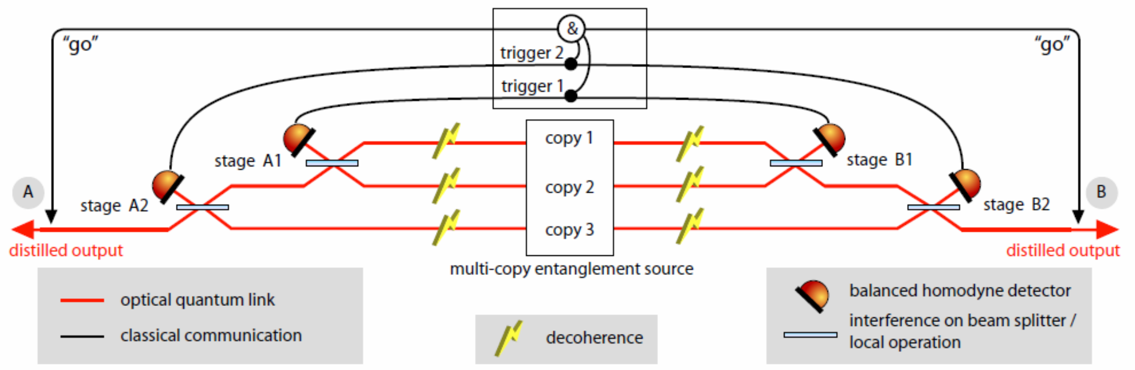

**Fig. 3:** *Collecitve free-copy Gaussification.*

A conceptual scheme of the collective three-copy Gaussification protocol is shown in Fig. 3. Four beam splitters were required to pairwise interfere the distributed parts of the three entangled copies for the two steps. Those in the first stage were balanced while those in the second stage provided a 2:1 power transmittance/reflectance ratio. Another four beam splitters were integral parts of the four balanced homodyne detectors (BHDs) which are shown in Fig. 3.

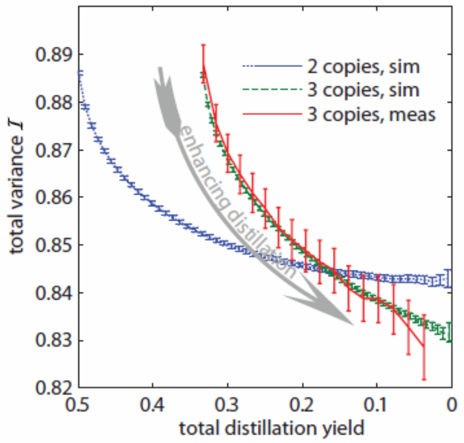

**Fig. 4:** *Total variance of the distilled states versus trigger threshold applied to both distillation stages.*

The total variance $I=\langle(\Delta x_A-\Delta x_B)^2\rangle+\langle(\Delta p_A+\Delta p_B)^2\rangle$ quantifying quantum correlations of the Gaussified state is plotted in Fig. 4. The state is entangled if $I<1$ and for pure two-mode squeezed vacuum we have $I=e^{-2r}$. The short dashed lines show the result of Monte Carlo simulations with the exact parameters of the experiment. The dotted lines represent the numerical simulation for the corresponding single-step two-copy protocol assuming exactly the same experimental parameters. The figure clearly illustrates that the three-copy iterative distillation can outperform the corresponding single-step two-copy protocol and it can provide lower output total variance $I$.

The theoretical proposal for simultaneous entanglement distillation and purification of Gaussian states together with the first experimental demonstration of three-copy iterative Gaussification protocol pave the way towards complete elimination of decoherence and suppression of losses in continuous-variable quantum information processing.

**Publications:**

Jaromír Fiurášek, *Distillation and purification of symmetric entangled Gaussian states*, Phys. Rev. A **82**, 042331 (2010).

Boris Hage, Aiko Samblowski, James DiGuglielmo, Jaromír Fiurášek, and Roman Schnabel, *Iterative Entanglement Distillation: Approaching the Elimination of Decoherence*, Phys. Rev. Lett. **105**, 230502 (2010).

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## Additional progress related to Deliverable 3.5:

*Entanglement Concentration Protocol for two macroscopic Atomic Ensembles*

(Partners USTAN)

The most promising protocol so far for potential use in Quantum Repeaters is shown by Julsgaard et.al. and uses 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 for the light mode can be defined. If two macroscopic atomic ensembles are held in magnetic fields it is possible to define quadrature operators similarly for the coherent spin states of the atoms. The interaction between the light and atoms then approximates a quantum non-demolition (QND) interaction. Julsgaard et al. were able to use this to entangle the macroscopic spin states of the two atomic ensembles. However the ensembles were only weakly entangled and so it is important to find ways to distill the entanglement in the system.

We have devised a protocol for increasing the entanglement between two entangled atomic ensembles based on applying an approximate atom-light beamsplitter transformation [1] to both ensembles. The effective asymmetric atom-light beamsplitter is created via a double-pass quantum non-demolition interaction between polarized light and a spin polarized atomic ensemble, derived from the linearised dipole interaction. The entanglement concentration protocol itself uses the procrustean method, similar to that first devised for light by Browne et al and includes photon counting after the interaction as the required non-Gaussian element (Fig. 1). The calculated output logarithmic negativity in this scheme provides evidence that entanglement between macroscopic ensembles can be increased with probabilities comparable with those for the light scheme [2].

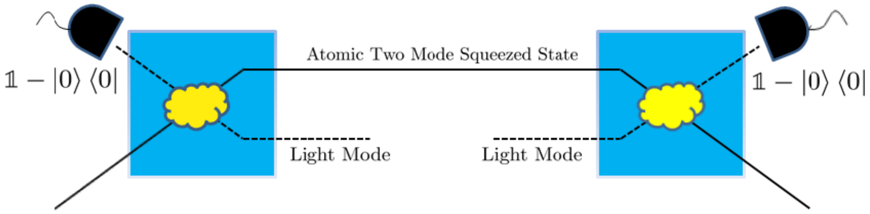

**Fig. 6.** *Procrustean entanglement concentration for atomic ensembles using QND interactions(exact or modelled as an effective atom/light beamsplitter using the double-pass scheme).*

Further, we have developed an improved scheme that uses no approximations and only a single pass, which demonstrates that entanglement distillation is possible using just pure QND interactions.

## Publications:

[1] R. Tatham and N. Korolkova, Phys. Scr. **T143** 014023 (2011)
[2] R. Tatham and N. Korolkova, submitted to J. Phys. B

## Conference Presentations:

R. Tatham and N. Korolkova, *An Entanglement Concentration Scheme for two macroscopic Atomic Ensembles*, 17th Central European Workshop on Quantum Optics (CEWQO 2009), June 6-11, 2010, St Andrews, Scotland (Poster).

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## Additional progress related to Deliverable 3.5:

*Continuous-variable distillation and Gaussification - the complete story*

(Partners POTSDAM)

At the basis for the known continuous-variable distillation schemes is a primitive operation that brings several modes together, and conditioned on a particular outcome, states become more entangled, purer, and also more Gaussian. At the time, it was unclear as to why exactly this Gaussian feature emerges, and in what generality such schemes could be applied. Remarkably, and apparently unrelatedly, there is also yet another deterministic scheme - one that had been used to show the extremality of Gaussian states - in which a collection of non-Gaussian states is deterministically transformed into a collection of Gaussian states with the same second moments.

New work by partner POTSDAM has now revealed that both types of protocols can be shown to work from the perspective of a more general mother protocol. At the basis of the argument, a new type of non-commutative central limit theorem is at work. In this way, the previously known schemes leading to Gaussian states could be unified.

What is more, a large class of new protocols could be identified, as the approach is general enough to accommodate for that. We consider new multi-partite protocols, interpolations of the above protocols, as well as distillation schemes with - experimentally motivated - a large acceptance window in homodyning. This general picture of continuous-variable entanglement manipulation should open up new paths to construct continuous-variable or hybrid quantum repeaters [1].

**Publications:**

[1] E. Campbell and J. Eisert, in preparation (2011).

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**Additional progress related to Deliverable 3.5:**
*Capacity of bosonic Gaussian channels*
(Partner ULB)

A central problem of information theory is to derive the capacity of communication channels, which is the maximal information transmission rate, for a given available energy. For classical information transmitted via quantum channels, this translates into finding the so-called classical capacity of the quantum channel. A particular interest has been devoted for a long time to Gaussian quantum channels with continuous encoding as they model common physical systems such as the transmission via free space or optical fibers. These channels belong to the general class of bosonic channels {1}, among which the most studied ones are the additive noise and lossy Gaussian channels (see e.g. {2,3 } and refs. therein). For these channels, it was also shown that correlated noise may lead to superadditivity in the sense that the transmission rate may be enhanced by input states with some degree of entanglement {4,5 }.

During the first two years of the project, partner ULB addressed the capacity of a Gaussian channel with memory (restricted to the usual Gaussian conjecture), modeled with an additive Markov correlated noise. Correlated Gaussian noise appears for instance in the models of downlink communications between satellites and terrestrial stations and a simple description of such correlations can be provided by an underlying Markov process. We found a *quantum water-filling* solution, similar to classical water-filling solution {6}. This is a surprising result since, unlike in the classical case, one has to take into account that a part of the input energy must be spent to the creation of quantum carrier states (squeezed states).

During the third year of the project, partner ULB pushed this analysis further. We derived a general solution to the Gaussian capacity of the Gaussian additive noise channel with noise correlations given by any stationary (shift invariant) Gauss processes. We showed that the method is applicable even to a larger class of noise models. We presented an algorithm for a numerical solution of the arising optimization problem tackled by the method of Lagrange multipliers. Using this method, we analyzed the capacity and the optimal input states and encoding as a function of the noise parameters for the example of the Gauss-Markov noise, including several limiting cases. For example, this method works in the input energy domain, even below the energy threshold that aroused in the previous analysis {6}, see Figure 1. In addition, we evaluated the enhancement of the transmission rate when using the optimal entangled input states by comparison with a product coherent-state encoding, and we found out that this simple coherent-state encoding achieves not less than 90\% of the capacity.

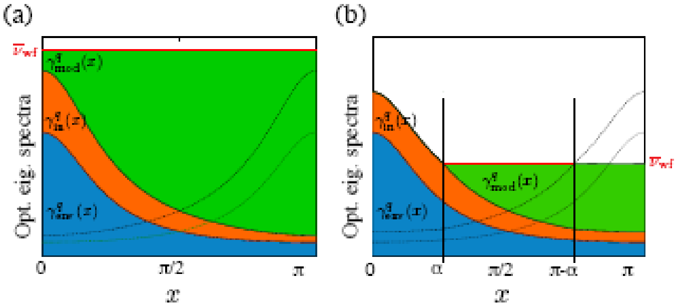

**Figure 1:** *Optimal input, modulation, and noise eigenvalue spectra for quadrature q (solid lines) and p (dashed and dotted curves) as a function of the spectral parameter x for a particular noise variance N and nearest-neighbor correlation φ. (a) Global quantum water-filling solution, where the red bar denotes the water-filling level. (b) Solution below threshold.*

**References:**

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Joachim Schäfer, Evgueni Karpov and Nicolas J. Cerf , *Quantum water-filling solution for the capacity of Gaussian information channels*, Proc. SPIE, Vol. 7727 (2010) 77270J.

**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]

N.J. Cerf, E. Karpov, J. Schäfer, *Information transmission in Gaussian memory channels: a quantum analogue of Shannon's water-filling solution*, 7th Workshop on Continuous-Variable Quantum Information Processing (CV-QIP'10), Herrsching (Ammersee), Germany, 11-14 June, 2010. [INVITED TALK]

J. Schäfer, *General Solution to the Capacity of the Gauss-Markov channel*, 7th Workshop on Continuous-Variable Quantum Information Processing (CV-QIP'10), June 11-14, 2010, Herrsching (Ammersee), Germany. [POSTER]

J. Schäfer, *Approaching the optimal rate of information transmission via a Gaussian quantum memory channel*, Photonics@be doctoral school 2010", March 28-30, 2011, Oostduinkerke, Belgium. [POSTER]

## 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 progress reported |
| D1.2 | Exploration of CV quantum computing with non-Gaussian quantum states | 1 | 7 | R | PU | 24 | Yes | 24 | Additional progress reported |
| D1.3 | Generation of high photon number Fock states | 1 | 7 | R | PU | 24 | Yes | 36 | Delivered jointly with D1.4 |
| D1.4 | Generation of monomode and multimode cat states | 1 | 7 | R | PU | 24 | Yes | 36 | Delivered jointly with D1.3 |
| D1.5 | Measurement-induced nonlinear operations | 1 | 7 | R | PU | 36 | Yes | 24 | Additional progress reported |
| D1.6 | Detector process tomography | 1 | 7 | R | PU | 24 | Yes | 24 | Additional progress reported |
| D2.1 | Engineering and manipulating states in atomic quantum memory | 2 | 8 | R | PU | 36 | Yes | 36 | Delivered |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| D2.2 | Light-atoms quantum interface for quantum information processing | 2 | 8 | R | PU | 24 | Yes | 24 | Additional progress reported |
| D2.3 | Interfacing light with atoms in optical lattices and trapped ions | 2 | 8 | R | PU | 24 | Yes | 24 | Additional progress reported |
| D2.4 | Alternative methods for generating non-Gaussian states using Kerr nonlinearity | 2 | 8 | R | PU | 24 | Yes | 24 | Additional progress reported |
| D2.5 | CV quantum repeaters based on complex quantum network geometries | 2 | 8 | R | PU | 24 | Yes | 24 | Additional progress reported |
| D3.1 | Cat-states implementation of the sign-flip operation | 3 | 9 | R | PU | 36 | Yes | 36 | Delivered |
| D3.2 | Assessment of the implementation of the C-NOT and Hadamard gates | 3 | 9 | R | PU | 36 | Yes | 36 | Delivered |
| 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 | – |
| D3.5 | Distillation or concentration of CV entanglement | 3 | 9 | R | PU | 36 | Yes | 12 | Additional progress 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 | | The work of partner POTSDAM (cfr. D 1.2) revealed that measurement-based quantum computing with CV Gaussian cluster states is not possible without employing the fully fletched machinery of fault tolerance, even when the resources and all measurements are perfect. This renders this approach highly impractical. It was therefore decided not to attempt the experimental generation of CV Gaussian cluster states and the experimental efforts were redirected towards quantum computing with cat-state gates. |
| MS3 | Generation and breeding of Schrödinger cat states of light | 1 | 7 | 24 | Yes | 36 | Achieved Y3 (single-photon subtraction and addition). |
| 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 | | The technical noise has so far prevented successful generation and observation of atomic Fock states, despite numerous efforts. In order to suppress the noise, several measures were implemented: the trapping laser was replaced by a DBR-diode followed by a fiber amplifier and a new excitation scheme using strong magnetic field and atomic clock transition was developed. Then, a new setup based on atoms trapped in the evanescent field of a tapered nanofiber was built. This latter approach requires much smaller number of atoms, which should result in a dominance of the projection noise over technical noise as well as in faster experimental cycle. Since these significant modifications required extra time, the atomic Fock state has not yet been generated at the time of preparation of this report. |
| MS7 | Experimental small-scale few-modes CV quantum processor | 3 | 9 | 36 | Yes | 36 | Achieved Y3 (experimental cat-state gates, noiseless amplifier). |

## 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 deliverables in WP4 during the third year of the project, except for the activity reports.

### Project website (Task 4.1)

The project website kwws=22rswlfv1xsro1f}2frp sdv2 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: *1$^{st}$ 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 *7$^{th}$ Continuous-Variable Quantum Information Processing workshop* was held in Ammersee (near Munich), Germany, June 11-14, 2010. It was organized by partner MPG during the third year of the project, and was one of the key conferences devoted to this topic in 2010. It was immediately be followed by the second year Project Review Meeting.

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

### 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 was held on an informal basis during the *7th Continuous-Variable Quantum Information Processing workshop* in Ammersee (near Munich), Germany, June 11-14, 2010.

### 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.

Finally, let us emphasize additional actions towards knowledge dissemination that were carried out during the third year of the project. Two review papers related to CV-QIPC were written, which should reinforce the visibility of CV-QIPC research:

- C. A. Muschik, H. Krauter, K. Hammerer, and E. S. Polzik, *Quantum information at the interface of light with mesoscopic objects*, arXiv:1105.2957 (2011). Contribution to the Quantum Information Processing special issue on neutral particles edited by R. Folman

This review paper, authored by partners MPQ and NBI, reports on the recent research towards a universal light-matter interface for quantum information processing (see also D2.2). Such an interface is an important prerequisite for long distance quantum communication, entanglement assisted sensing and measurement, as well as for scalable photonic quantum computation. The developments in light-matter interfaces based on room temperature atomic vapors interacting with propagating pulses via the Faraday effect are reviewed. This interaction has long been used as a tool for quantum nondemolition detections of atomic spins via light. It was discovered recently that this type of light-matter interaction can actually be tuned to realize more general dynamics, enabling better performance of the light-matter interface as well as rendering tasks possible, which were before thought to be impractical. This includes the realization of improved entanglement assisted and backaction evading magnetometry approaching the Quantum Cramer-Rao limit,quantum memory for squeezed states of light and the dissipative generation of entanglement. Moreover, a possible interface between collective atomic spins with nano- or micromechanical oscillators is reviewed, providing a link between atomic and solid state physics approaches towards quantum information processing.

- C. Weedbrook, S. Pirandola, R. Garcia-Patron, N. J. Cerf, T. C. Ralph, J. H. Shapiro, and S. Lloyd, *Gaussian Quantum Information*, submitted to Rev. Mod. Phys. (2011).

This review paper, authored by partner ULB together with several collaborating groups, focuses on the CV quantum information processes that rely on any combination of Gaussian states, Gaussian operations, and Gaussian measurements. Interestingly, such a restriction to the Gaussian realm comes with various benefits, since on the theoretical side, simple analytical tools are available and, on the experimental side, optical components effecting Gaussian processes are readily available in the laboratory. In fact, a little over a decade ago, when Gaussian quantum information protocols were beginning to be developed, it was considered unlikely that they could be really powerful given that the Wigner function of a Gaussian state is positive everywhere. The lack of counter-intuitive "negative probabilities" seemed to imply that Gaussian quantum states were almost classical, hence useless for quantum information processing. Nonetheless, Gaussian states and operations are now being recognized as key resources for quantum information processing, on the same level as quantum bits and traditional quantum, and Gaussian quantum information processing has proven to open the way to a wide variety of tasks and applications. This review reports on the state of the art in this field, ranging from the basic theoretical tools and landmark experimental realizations to the most recent successful developments.

### 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 roadmap ("reflection paper") on the outlook of the research in continuous-variable 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 *CV-QIPC roadmap* can be found in the Appendix of the present activity report (cf. Section 7).

It is based on brainstorming sessions that were organized during previous CV-QIP workshops, and mainly on the outcome of the COMPAS "roadmap meeting", which took place in Hôtel Le Dôme, Brussels, November 30th – December 1st, 2009. Although it is aimed at providing a broad overview of CV-QIPC research, the positioning and specific achievements of COMPAS research is highlighted.

## 6. Appendix A: Explanation of the use of the resources

The detailed explanation of the major cost items for each partner will be attached to the financial report and uploaded directly to the NEF platform.

## 7. Appendix B: Roadmap on continuous-variable QIPC

The roadmap on continuous-variable QIPC will be 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.