PROJECT FINAL REPORT

Publishable Summary

Grant Agreement number: 212008

Project acronym: COMPAS

Project title: Computing with Mesoscopic Photonic and Atomic States

Funding Scheme: CP-FP-INFSO

Period covered: from 1st April 2008 to 31st March 2011

Name of the scientific representative of the project's co-ordinator, Title and Organisation:

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

Tel: +32 2 650 28 58

Fax: +32 2 650 29 41

E-mail: ncerf@ulb.ac.be

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

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 known 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 two 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.

COMPAS is a Specific Targeted Research or Innovation Project (STREP) aimed at exploratory research on mesoscopic continuous-variable (CV) quantum information systems, both on the theoretical and experimental sides, with the objective of making major steps towards the first small-scale quantum processor using this CV paradigm. In the recent years, the 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 in the past 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 been further 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. COMPAS was dedicated to the exploration of these spectacular achievements in a focused research project. In interplay between theory and experimental research, the COMPAS consortium investigated the hitherto essentially unexplored potential of CV quantum computing and addressed the necessary steps on the way to mesoscopic CV processors. The main research lines pursued in COMPAS included the development of elementary gates for CV quantum computing with cat states, CV entanglement distillation, CV quantum error correction, and the design of CV quantum repeater architectures. Harnessing non-Gaussian quantum states was an absolute prerequisite in order to reach these goals, so that a strong effort was dedicated to the engineering of non-

Gaussian operations. A number of breakthroughs were achieved during the course of the project, witnessed by many publications in high-impact scientific journals.

As illustrated in the following table, the project consortium was 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 comprised scientists who had been largely involved in the development of continuous-variable quantum information processing. This strong complementarity ensured that the theoretical ideas developed in the course of the project were demonstrated by the experimental groups in a close collaboration. As a matter of fact, virtually all main research tasks within COMPAS were carried out jointly by theorists and experimentalists. This strong interplay between theory and experiments illustrated the need for a supra-national collaborative scale in order to reach the ultimate project objectives.

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

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

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

Major achievements

The concrete objectives of COMPAS were to experimentally demonstrate several quantum information processing tasks such as quantum gates for CV quantum computing, CV entanglement distillation, and CV quantum error correction, which represent fundamental steps on the way to mesoscopic CV quantum processors. Such small processors in which several photonic and/or atomic modes would interact in a controlled manner could, for instance, form the nodes of advanced quantum communication networks. The most significant achievements of COMPAS are summarized below.

Quantum gates for cat-states CV quantum computing

A major goal of COMPAS was to demonstrate quantum gates with CV carriers of quantum information. In this context, the concept of cat-state quantum computing, in which the qubits are encoded into superpositions of two coherent states, emerges as a particularly promising candidate for proof-of-principle experimental tests. As a first step in this direction, a simple approach to generating strongly entangled nonlocal superpositions of coherent states by nonlocal photon subtraction from two distant squeezed vacuum states was successfully demonstrated, using a very lossy quantum channel. Such superpositions should be useful for implementing coherent qubit-rotation gates and for teleporting these qubits over long distances. The generation scheme may be extended to creating entangled coherent superpositions with arbitrarily large amplitudes.

The main advantage of optical cat-state CV quantum computing is that two-qubit entangling gates can be in principle implemented deterministically by interference on a beam splitter. However, a fully scalable scheme requires photon parity measurements to avoid information leakage out of the computational subspace. Another 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 that transforms coherent states onto their superpositions (odd or even cat states). Reliable photon number parity measurement is extremely hard to implement even with cryogenic photon counters (VLPC) capable of resolving the number of photons. The use of these VLPCs was thoroughly experimentally investigated within COMPAS.

These difficulties were overcome by devising a novel simplified experimentally feasible schemes for implementation of single- and two-qubit quantum gates with the cat-state qubits. The driving force of all these gates is the well-mastered single-photon subtraction. This theoretical proposal was very soon followed by two experimental demonstrations of this scheme by COMPAS members. First, the elementary sign-flip operation that transforms an even cat to an odd cat and vice versa was implemented. Remarkably, this manipulation can be conditionally accomplished simply by subtracting a single photon from the state. Second, the challenging Hadamard gate was experimentally demonstrated. The gate requires an ancilla even cat-like state that was in the experiment approximated 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 at this time it is combined with coherent displacement of the input state and conditioning on the outcome of a homodyne measurement of one of the output modes. These results represent one of the major achievements of COMPAS. They clearly confirm the feasibility of quantum gates for cat-like states and pave the way toward more complex quantum information processing schemes based on qubits encoded into superpositions of coherent states.

Heralded noiseless amplification of light

An intriguing concept closely related to the quantum information processing with superpositions of coherent state is the so-called heralded noiseless amplification of light. The noiseless amplifier is a device that conditionally increases the amplitude of coherent states without adding any extra noise. It could be used for amplification of cat states formed by superposition of two coherent states, which could greatly facilitate future realization of cat-states quantum computing schemes. Moreover, noiseless amplification has many potential applications in advanced quantum communication schemes because it can be utilized for continuous-variable entanglement concentration or probabilistic high-fidelity cloning of coherent states, while it can also conditionally improve the distinguishability of coherent states. A modified version of the noiseless amplifier can even emulate Kerr nonlinearity that is essential for designing certain CV quantum gates.

As an important step towards the development of basic operations for CV quantum computing, several experimental implementations of the probabilistic noiseless amplifier for weak coherent states were demonstrated by COMPAS. The first experiment was based on the quantum scissors scheme. The amplifier exhibited negative equivalent input noise and a nominal amplitude gain $g=2$ (this gain decreases with increasing amplitude of the input coherent state). However, the quantum scissors are based on state truncation which limits the performance of this scheme. Therefore, a refined amplification scheme was developed based on coherent combination of photon subtraction and photon addition. Such noiseless amplifier was even further simplified by replacing the single-photon addition by addition of thermal noise, which is much easier to implement experimentally. The resulting amplifier adds some little noise, but it can still strongly improve the phase resolution in experiments with coherent states. These theoretical schemes were subsequently successfully demonstrated experimentally, thus adding the high-fidelity heralded noiseless amplifier in to the CV quantum information processing toolbox.

CV entanglement distillation and quantum error correction

Besides quantum gates and quantum computers, another important example of a quantum processor is a quantum repeater, whose central part consists of entanglement distillation. Therefore, the COMPAS consortium focused on designing and demonstrating advanced schemes for distillation of CV entanglement and CV quantum error correction. The distillation of deterministically prepared entangled light pulses that have undergone non-Gaussian noise was achieved in two experiments. In the first work, the pulses travelled through a lossy channel, where the transmission varies in time similarly to light propagation in the atmosphere. By employing linear optical components and global classical communication, the entanglement of the state was probabilistically increased. Secondly, in collaboration with the group of Prof. R. Schnabel at Albert Einstein Institute in Hannover, the COMPAS consortium also realized the entanglement distillation and purification of phase-diffused two-mode squeezed states using interference on beam splitters and homodyne detection. In both experiments, the measurements clearly indicated a regained strength of entanglement and purity of the distilled states. The schemes demonstrated the actual preparation of the distilled states, which might therefore be used to improve the quality of downstream applications such as quantum teleportation. The latter experiment was even extended to the first experimental demonstration of collective three-copy entanglement distillation of two-mode CV entangled states. This experiment unambiguously demonstrated the advantage of collective multi-copy entanglement distillation schemes. On the theory side, a nested distillation protocol for Gaussian states was proposed that simultaneously distills entanglement and purifies the states and provably 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 a non-Gaussian quantum filters. This is an example of exploitation of the tools developed in COMPAS for more complex quantum information tasks.

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

All these achievements pave the way towards long distance CV quantum communication networks and CV quantum repeaters.

Quantum memories

Reliable long-lived quantum memories represent a crucial component of quantum repeater architectures. An important part of project COMPAS was thus a study on the preparation and manipulation of quantum states of atomic information carries, in particular atomic memories formed by ensembles of alkali metal atoms. On the way towards quantum memory with cold atoms, a low noise measurement of one component of the collective pseudo-spin of a cloud of 10^5 cold and dipole trapped Caesium atoms was demonstrated using a novel dual-color interferometric probing technique that allows for the cancellation of numerous classical noise sources. Using this technique, the atoms were prepared in a strongly entangled collective squeezed state that can be used to improve quantum precision measurements or can serve as a low noise initial state for a quantum memory protocol. The performance of the atomic memory was then optimized by suppressing technical noise induced by a microwave reference oscillator by constructing a low phase-noise microwave synthesizer chain. A tomography microwave pulse sequence was developed that is robust against coupling inhomogeneities and can be used for complete characterization of atomic memory state. A full squeezing-enhanced atomic clock protocol was implemented that over short integration time performs better by 1.1 dB compared to standard Ramsey spectroscopy.

Furthermore, quantum memories formed by ensembles of hot atoms held in a glass cell were investigated in depth. A refined theoretical model of atoms-light coupling taking into account tensor terms in the interaction Hamiltonian was developed. This model enabled more effective optimization of the memory protocol. Pre-squeezing of the atomic state was used to decrease the noise in quantum storage scheme. Storage of entangled two-mode squeezed states of light was successfully demonstrated, outperforming any possible classical memory scheme. An intriguing method for the preparation of various states of quantum memory via engineered dissipative light-matter interaction was also experimentally verified. Using this method, EPR-type entanglement between two atomic memories was generated and maintained for 0.04 s. Using continuous measurement on the output light then resulted in the generation of steady state entanglement of atomic memories observed for up to an hour. This concept could be used to construct a dissipation-driven quantum repeater.

An EIT-based three-level adiabatic passage protocol for quantum memory using a Caesium vapour in a cell was also developed. Quantum storage and retrieval of faint coherent pulses of light, made of a single sideband of the control field, was successfully demonstrated. Due to complicated internal level structure of Caesium, the inhomogeneous broadening can be very detrimental to memory operation. This negative effect can be suppressed by two orders of magnitude by cooling the atoms and an effective cooling mechanism through an engineered optical pumping was proposed for this purpose. In parallel, an alternative setup for memory that is based on cold Cs atoms held in a magneto-optical trap and completely avoids the problems associated with room-temperature Doppler broadening was designed. The resulting quantum memory exhibits storage time of 1 μs and efficiency of 11%, which could be further improved by laser pulse shaping.

Other achievements and conclusion

The project COMPAS also resulted in many other related outcomes that are described in length in the three periodic activity reports, so that they are not repeated here. Let us only briefly mention the first experimental tomography of a quantum detector, development of new sources of squeezed and entangled light, important theoretical results on CV one-way quantum computing, or the theoretical design of novel CV quantum repeater architectures. In total, 120 scientific papers were produced by the COMPAS consortium during the entire project, among which 32 in Physical Review Letters, 6 in Nature Physics, 2 in Nature Photonics, and 1 in PNAS. Numerous very fruitful collaborations were run between different subgroups of the consortium, systematically involving at least one experimental and one theoretical group. This is reflected by the large fraction of joint articles during the project.

The challenges addressed within COMPAS meet the broader vision of our future ICT-based society. As illustrated by the above description of its major achievements, COMPAS opened novel directions to the physical realization of ICT-related technologies, which could, in the long term, induce a qualitative boost in the computing and communication capabilities of computer networks. Its possible societal impact may thus result from the future transfer of the basic science results towards new schemes and/or devices for quantum computing. This may lead to a considerable progress in information technologies and contribute to the future international competitiveness of the European industry in this field.