Roadmap on
Quantum Information Processing and Communication with Continuous Variables
(CV-QIPC)

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Contents:

Introduction

This document supplements the "*QIPC strategic report*" by elaborating on the topic of continuous-variable quantum information processing, which was only briefly touched upon in there. It covers the topics which were (or are) investigated in the main European projects especially devoted to CV-QIPC, namely QUICOV 2000-2003, COVAQIAL 2004-2007, and COMPAS 2008-2011, but also treats the progress of this field worldwide.

I. General definition of continuous variables (CV)

Definition of "*CV-QIPC*": information processes involving carriers with continuous degrees of freedom, such as the quadratures of light or collective atomic degrees of freedom [1],[2]. Typically, homodyne detection for light (or measurement of canonical variables for atoms) is used for characterizing the states or for processing them (deterministic feed-forward). In CV processes, one typically uses a physical support (photonic or atomic) where the number of photons or atoms is not bounded (unlike a photonic qubit, for instance, where one has a single photon whose polarization is carrying information [3]).

Definition of "*mesoscopic*": a photonic cat state [4] (or even a vacuum squeezed state, which is an approximation to an even kitten state) is somehow half way between a microscopic and a macroscopic object (this is because we observe a quantum superposition effect for a large number of photons). In the case of atoms, it can be seen as a collective state of an ensemble of atoms, where excitations are distributed among a large number of atoms, which makes the encoding robust with respect to the atom losses or decoherence [5]. (An enlightening analogy is the W-state of many qubits, whose entanglement is preserved even if several qubits are lost or decohere.) In the case of light, the joint (2-mode) state of the signal mode and the orthogonally polarized strong coherent local oscillator can be seen as a collective polarization state of many photons.

Definition of a "*CV-based quantum processor*": it is manipulating quantum information encoded in continuous degrees of freedom, either of light or of atomic ensembles. Its goal is to implement elementary quantum algorithms or information processing tasks, such as a quantum repeater node, using CV quantum operations, gates and quantum circuits.

Using continuous variables comes with several generic advantages. First, one can use nearly perfect detectors (homodyne detection can have an efficiency exceeding 98% and electronic noise less than 20 dB below the shot noise) [2]. Second, one has the possibility to probe the collective state of an atomic ensemble by performing highly efficient QND measurements [5]. This also provides efficient and deterministic interfacing between light and matter, which makes distributed quantum computing possible (any process requiring a quantum memory is enabled). Processing information encoded in atomic degrees of freedom is significantly more robust when using CV in the sense that no high-Q cavity is needed to provide a high interaction strength in the ensemble (one has a collective enhancement). Finally, many key operations can be performed in a deterministic fashion, which is particularly interesting for light. By comparison, quantum gates on single-photon qubits using linear optical techniques are necessary probabilistic because there is currently no strong enough nonlinear coupling between photonic qubits [3].

When dealing with CV, there is a crucial distinction between Gaussian and non-Gaussian states and operations. Multimode Gaussian states and operations can be characterized in a very compact way, based on the first- and second-order moments. On the good side, these states and operations can be very efficiently realized in the lab (using passive linear optics and squeezers, supplemented with homodyne detection + feedforward, and QND coupling between light and atoms) [1]. This toolbox enables many interesting CV-QIPC tasks, such as QKD [6], teleportation [7], entanglement swapping [8], and dense coding. On the other hand, this also means that Gaussian states and operations can be efficiently simulated on a classical computer because the complexity scales only quadratically with the number of modes [9]. Thus, CV quantum computation within the Gaussian framework does not have any competitive advantage over classical computers. Another intrinsic limitation is that entanglement cannot be distributed over long distances with Gaussian operations alone (quantum error correction or entanglement purification is impossible with Gaussian operations [10],[11],[12]). All these limitations can be overcome by exploiting the non-Gaussian states and operations, as we will see.
Similarly to the case of discrete variable processes, an efficient (scalable) realization of CV processes can only be achieved if quantum memories are available. The mastering of the light-matter interface for continuous variables is a competitive advantage of CV QIPC [5]. In the case of CV quantum communication, a quantum repeater is required to fight losses and decoherence, which eventually requires a quantum memory within the entanglement purification protocol. Another

scheme that requires a quantum memory is quantum illumination [13]. For CV quantum computing, a first obvious reason why one needs quantum memories is that one cannot use flying optical information carriers; one must use material carriers. This is particularly true for one-way CV quantum computing, which requires storing a CV cluster state in a multimode quantum memory [14]. Secondly, to achieve an efficient scaling of the success probability, a quantum memory is always necessary.

A first way to implement an atomic quantum memory relies on an ensemble of atoms held in a glass cell (at room temperature) or cold atoms in a trap [5]. Today, this has been the most promising approach. However, there are interesting alternatives such as impurities in solid state matrices [15]. Here again, it is a collective state of many atoms which forms the memory.

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II. CV quantum communication

Historically, the development of CV-QIPC has concerned primarily the implementation of quantum communication protocols. The first reason for this is that the field of (classical) coherent optical communication was already well developed, so that a natural idea was to exploit the high bandwidth of homodyne detection in the quantum regime. The first communication protocol which was put forward with CV is quantum teleportation. This was demonstrated in 1998 by the group of H. J. Kimble (Caltech), and triggered the expansion of CV-QIPC [1],[2].

II.1 Point-to-point QKD (short term)

Today, the most developed CV quantum communication protocol is undoubtedly quantum key distribution. Many protocols have been devised since the early 2000's, based on squeezed, entangled, or even coherent states [3],[4]. Since it was shown that coherent states are sufficient to ensure security, most of the effort was focused on improving the coherent-state protocols and on developing more general security proofs [5]. Today, the security of the Gaussian-modulated coherent-state protocol has been proven against individual, collective, and coherent attacks [6],[7],[8]. However, the current proof against coherent attacks is not ideal in the sense that the rate that is proven secure is low (this is because Gaussian attacks do not play a special role in the proof, while they are known to be the optimal individual and collective attacks). An important endeavor is thus to develop new techniques to prove the security against coherent attacks, in particular based on the quantum de Finetti theorem or on the post-selection technique. Another main challenge in the field of CV-QKD is to find new techniques to improve the range, which was initially the weak point of CV-QKD. The reason is that the line loss-induced vacuum noise creates errors, which are difficult to correct. The current experimental state of the art is the distribution of secret keys at a rate of 2 kbps over 25 km (or 10 kbps over 10 km). Recent theoretical work has shown that the range of CV-QKD can be significantly extended using a discrete low-variance modulation protocol supplemented with an improved reconciliation algorithm. This still has to be verified in the laboratory. In addition, further theoretical progress is still expected in this direction as the current protocols are most probably not optimal.

II.2 Teleportation, towards quantum repeaters (long term)

The major limitation of the range of CV-QKD is the line losses, which one has to fight with to enable long-distance quantum communication. The standard way towards long ranges consists in implementing a continuous-variable quantum repeater. A quantum repeater is a device in which entanglement swapping between neighboring nodes is used to extend the distance over which entanglement is distributed. Every node of the repeater is an elementary quantum processor. Thus, as for discrete variables, three elements must be harnessed, namely entanglement purification, entanglement swapping, and quantum memories. The fact that atomic quantum memories are well suited for the storage of CV states of light makes the research on CV quantum repeater particularly promising [9]. Furthermore, the fact the entanglement swapping can be performed deterministically with CV (in contrast with discrete variables) makes this even more promising [10],[11]. However, a blocking issue is that the entanglement purification is impossible in the Gaussian regime [12],[13],[14], which implies that non-Gaussian procedures need to be invented and developed. Several proposals for CV entanglement purification have been experimentally demonstrated over the last years [15],[16],[17], but this issue still remains the main challenge towards a CV quantum repeater. Of course, there is also the need for improving the quantum memories that are expected to be used in this context (enable readout as well as storage, and increase the lifetime).

An alternative method to fiber-based CV-QKD is to turn to free space transmission. An advantage of CV here is that homodyne detection provides a very efficient filtration (only the mode which is matched to the local oscillator gives rise to a signal), which allows high-rate communication in day light. This avenue deserves being further investigated.

II.3 Quantum error correction

A first result is that no quantum error correction in a Gaussian channel can be achieved solely with Gaussian operations [18]. On the other hand, non-Gaussian errors, such as erasures (probabilistic signal loss) or phase fluctuations, can be suppressed by Gaussian protocols [19],[20],[21]. An important open question in this context is whether non-Gaussian states can be protected from Gaussian errors by Gaussian operations.

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III. CV quantum computing

The notion of universal quantum computing is much less developed for CV information carriers than for discrete-variable ones. The first result in this direction originates to Braunstein and Lloyd, who showed that Hamiltonians of at least third order in the quadrature operators are necessary and sufficient for universal computing [1]. In other words, manipulating quadratic Hamiltonians (i.e., passive linear optics + amplifiers and squeezers) is insufficient to achieve universal computing. This is the key reason why a large fraction of the activity in CV-QIPC has been focused either on ways to achieve optical nonlinearities (either directly via Kerr effect, such as giant nonlinearities, or induced by non-Gaussian measurements, such as photon counting) or on the preparation and processing of non-Gaussian states such as cat states.

An issue that must be emphasized is that the main goal of CV quantum computing is to find clever ways to embed qubits into CV Hilbert spaces, and to apply to them the standard quantum gates in order to perform quantum algorithms. In other words, it is not the algorithms that become continuous; it is rather the carriers of quantum information. The thrust is that carrying qubit-like information in CV systems may facilitate the realization of gates, the storage, and the measurements.

Let us review the currently envisaged models for CV quantum computing. One promising model of CV processor is based on cat states, which allow for instance simple implementations of 2-qubit gates. Other possible models for CV quantum computing include cluster states, or dissipation-induced quantum computing.

III.1 Circuit-based quantum computing (cat-state gates)

The circuit-based quantum information processing with continuous variable coherent superposition states (cat states) has been theoretically proposed and developed in the past few years by T. Ralph and collaborators [2],[3]. The advantage of this approach is that it requires only linear optical operations provided that off-line cat states are available. The two-qubit controlled sign gate can be implemented deterministically just by interfering two cat states on an unbalanced beam splitter. The only difficult operation within this framework is the Hadamard gate, which amounts to the generation of coherent superposition states from ordinary coherent states. It can be realized with off-line generated auxiliary cat states and measurement.

Currently, small optical cat states (kitten states) of propagating light modes can be generated experimentally by subtracting a single photon from squeezed vacuum state or by performing partial homodyne detection on a conditionally prepared Fock state [4],[5][6]. Local and even nonlocal superposition of cat states can also be prepared by similar methods [7]. These procedures were originally developed and mastered by European researchers, so Europe is currently at the forefront of the experimental research in this area.

The main present challenge is to demonstrate the elementary single-qubit and two-qubit gates for such cat-state qubits. Since any currently foreseeable method of cat-state generation will be probabilistic (unless giant optical nonlinearities become available), for this approach to be scalable it is mandatory to store the generated cats in quantum memories. The generation of cat states (or even small kitten states such as squeezed Fock states) in a quantum memory is thus another crucial short-term goal.

In the long-term perspective, techniques for preparing large enough superposition states have to be pursued and established to reach a regime where the errors due to finite size of the cat state become sufficiently small so that they can be tackled with quantum error correction or fault-tolerant schemes. Experimentally, this will require sources of pulsed squeezed light with significant squeezing and very high purity, photon number resolving detectors with very high detection efficiency (e.g. transition edge sensors or VLPCs), and efficient quantum memories with long storage times. Sensitivity of this computing scheme to various imperfections needs to be carefully analyzed. Thus, there is need for theoretically developing robust methods and protocols that can protect the CV states from errors and decoherence during the computation.

III.2 Measurement-based quantum computing

An alternative model for quantum computation is the measurement-based quantum computation. As for discrete variables, measurement-based CV quantum computing is based on the prior preparation of a massively entangled multimode quantum state, which may or may not be Gaussian, followed by a sequence of measurements on each mode which depends on all previous measurement outcomes. In the standard approach, this CV cluster state is Gaussian, so that the applied measurements need to be non-Gaussian in order to produce a non-Gaussian overall evolution.

In this measurement-based approach, universal quantum computation can be realized by single-mode measurements on a highly CV entangled state. Present proposals concern with the preparation of a CV cluster state where multimode Gaussian operations can be implemented by single-mode quadrature measurements while universal QC requires non-Gaussian measurements [8],[9]. The implementation of CV graph states using optical devices seems very promising [10],[11], where Gaussian operations are performed by homodyne detection, but the implementation of non-Gaussian operations remains a challenge. Thus, future directions of research in this field involve the analysis of other resources states, such as non-Gaussian states, where it would be possible to implement universal QC with a few efficient measurements.

III.3 Unconventional quantum computing strategies

III.3.a Dissipation-induced quantum computing

Dissipative evolutions are a novel (long term) tool for quantum state engineering [12],[13],[14],[15], and can be used to produce extremely long-lived CV entangled resource states such as two mode squeezed states. Interestingly, the typical type of dissipation in optical CV systems (coupling to the vacuum) is quite entanglement-friendly in the sense that it is "entanglement long-life" rather than "sudden-death".

Moreover, quantum dissipative evolutions have been shown to allow for efficient universal quantum computation [12]. This new approach is inherently robust, as the result of the computation is encoded in the steady state of the evolution. It would be very interesting to extend this promising approach from the discrete to the continuous domain. In particular, it would be interesting to investigate what can be done using a restricted toolbox such as operations that can be realized experimentally with current technology. Even if universal quantum computation is not possible under the given restrictions, a useful subset of quantum algorithms or the efficient solution for a specific problem may be within reach.

III.3.b Engineering of linear and nonlinear operations (e.g., emulation of noiseless amplifier, Kerr nonlinearity)

The range of CV quantum operations that are directly experimentally accessible is rather limited. Even squeezing of an arbitrary state of traveling light mode, such as single photon or cat state, is experimentally challenging due to need for a very good mode matching in a nonlinear crystal. Remarkably, it has been shown that the squeezing and CV QND coupling can be emulated using off-line generated squeezed vacuum states, passive linear optics, homodyne detection and feed-forward. In this way, arbitrary Gaussian operation can be implemented deterministically [16]. Proof-of-principle experiments have already verified the feasibility of this approach [17],[18]. To fully exploit the potential of this method and achieve high-fidelity performance, sources of pure strongly squeezed states should be developed.

Going beyond the realm of Gaussian operations, it has been realized recently that combination of photon subtraction and addition enables to emulate various important interactions. Of particular interest is the probabilistic noiseless amplifier which increases amplitude of coherent states without adding noise [19],[20],[21],[22],[23]. Such amplifier may facilitate CV entanglement distillation and concentration and potentially increase security of quantum cryptography. Kerr nonlinearity is another important interaction that can be simulated by this method. The emulation of nonlinear interactions can facilitate quantum computing with qubits embedded in CV Hilbert spaces and may pave the way toward implementation of CV quantum simulators. A short term goal in this research area is to demonstrate the theoretically proposed concepts experimentally and verify their viability. In the long-term perspective, optimal schemes for high-quality emulation of various nonlinear CV operations that minimize the necessary resources and maximize success probability need to be identified theoretically and realized experimentally. It is likely that efficient simulation schemes will require quantum memory.

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IV. Resources

IV.1 Sources of squeezed and entangled states

Many quantum information protocols are based on a supply of efficiently squeezed states of light. Although such states of light have been generated for more than 20 years, significant progress on the production of very pure and highly squeezed states has been reported only recently. All demonstrations of highly squeezed states have utilized either the second-order nonlinearity via optical parametric amplification or the third-order nonlinearity in the silica of optical fibers or atomic vapor.

To date the most successful approach for squeezed light generation is by use of optical parametric amplification. Mediated by a second-order nonlinear crystal such as $LiNbO_3$, $KNbO_3$ or KTP (or periodically poled versions), a pump photon can break up into two photons which are entangled in many degrees of freedom. E.g. they are quadrature entangled and if the two photons are indistinguishable, the quadrature correlations lead to quadrature squeezing. In order to produce highly squeezed states, different efficiency-enhancing approaches have been pursued. One approach is to apply powerful short optical pulses as a pump field and another approach is to use optical waveguides, which prevents the optical pump field from diffracting inside the nonlinear crystal. However, the most common approach to enhance the effective non-linearity is to place the nonlinear crystal inside a high-quality optical cavity in which the squeezed field is resonantly enhanced. Such an approach was used in the very first demonstration of squeezed light from a second-order nonlinear crystal and it is still the best approach. Through careful system optimization, the state of the art experiments produce more than 9dB squeezing in a ring-cavity consisting of a periodically poled KTP crystal [1] and more than 11 dB squeezing in a linear cavity based on a $LiNbO_3$ crystal [2],[3].

Squeezing of the optical field was observed for the first time in 1985 by Slusher et al who used the third-order nonlinearity in sodium vapor inside an optical cavity [4]. New experiments on atomic vapor squeezing have recently been setup [5],[6],[7] due to the need for narrowband squeezed light in some quantum informational protocols such as atomic memories.

The Kerr effect in silica fibers (based on a third-order nonlinear process) has also been successfully used to produce highly squeezed states. Because of the small value of the third-order susceptibility of silica, strong pulses and long fibers have been employed to produce a large enough nonlinearity to generate highly squeezed states. The first fiber squeezing experiment reported only 0.6 dB squeezing, but due to new refined methods and systems nearly 7dB squeezing has now been produced [8],[9]. Fiber squeezing experiments have the advantage that they need less demanding locking techniques and no cavities are involved. However they have been suffering from guided acoustic wave Brillouin scattering which renders the resulting squeezed state in a highly mixed state. This is in contrast to optical parametric amplification experiments where nearly pure states have been produced.

Common for the most efficient squeezing implementations mentioned above is that the experimental setup is very complex; it relies on the careful alignment, mode-matching and phase locking of several optical beams. Misalignments and phase instabilities may degrade the performance of the squeezed light source dramatically, and thus a future goal is to develop new systems and methods which are less depending on phase stability and mode-matching but at the same time are not compromising purity and squeezing efficiency. Higher stability might be obtained in integrated optical structures. Such an approach will possibly lead to improved process performance via better mode-matching and phase stability. A fully integrated solution also easily allows for miniaturization and scalability, properties which are not feasible with the present approaches.

Another line of research is to investigate new types of materials and new types of phase matching approaches for enlarging the effective nonlinearity and tailoring the squeezing spectrum. New types of low-loss resonators could also be explored: either new versions of the exiting large resonators or new miniaturized resonators that would allow for scalability. For systems utilizing the Kerr effect in optical fibers the usage of photonic crystal fibers and different nonlinear materials could increase the purity of the squeezed states.

In all of the above mentioned systems one can in addition extend the number of degrees of freedom that are used for the squeezed state generation. Multimode squeezing in the spatial, frequency or polarization domain delivers richer possibilities for CV-QIPC in higher dimensional Hilbert spaces [10],[11].

IV.2 Sources of non-Gaussian states

(e.g., sources of kitten, and cat states)

In the recent years, there have been extensive studies to generate non-Gaussian states of light using measurement-induced state preparation. Basic tools are entangled EPR beams, also called two-mode squeezed light, or “twin beams”. Typically, a quantum measurement in one of these beams projects the other one in a known quantum state. For instance, a photon counting measurement (“one click”) will project the other beam in n=1 Fock state, and two clicks will project in a n=2 Fock state. With appropriate filtering, these states are prepared in single modes, and their (negative and non-Gaussian) Wigner function can be reconstructed using homodyne detection and quantum tomography [12],[13]. Other techniques are photon subtraction [15],[16],[17] (from a squeezed state), photon addition (to a coherent state) [14], as well as many variants, including for instance the preparation of entangled non-Gaussian beams using non-local photon subtraction [18].

Presently, photon subtraction up to n=3 has been performed in the pulsed regime, generating “Schrödinger’s kittens” of growing size [15],[19]. Similar experiments have been realized in the quasi-CW regime, and may be well adapted to interfacing with atomic memories [16],[17]. There are also proposals of using such techniques for generating “measurement induced” non-linearities, including Kerr effect and cubic phase gates. The next step is to use these techniques to implement simple quantum operations or algorithms, such as quantum gates in the “cat state quantum computing” approach, or non-deterministic noiseless amplification [20], or quantum information protocols including “loophole-free” tests of Bell’s inequalities [21],[22].

IV.3 Atomic quantum memories

An interface between quantum information carriers (quantum states of light) and quantum information storage and processors (atoms, ions, solid state) is an integral part of a full-scale quantum information system. In quantum information processing simple classical detection of light is inadequate for recording into memory, because it destroys the quantum state by adding extra noise to it. Hence a quantum interface has to be developed that enables coherent storage and retrieval of quantum states of light. The quantum memory is a crucial ingredient for quantum networks, and is indispensable e.g. for construction of quantum repeaters.

Continuous-variable quantum information processing requires quantum memories that are capable of storing a full quantum state of an optical mode or pulse, not only a state of a single photon. The CV quantum memories benefit from collective enhancement of the matter-light coupling, which provides strong coupling even without optical cavities. The first experimentally demonstrated quantum memory was based on a quantum non-demolition coupling of a light beam with an ensemble of Cesium atoms held in a glass cell at a room temperature [23]. The achieved quantum state storage time of up to 4 msec corresponds to propagation time over a distance of about 1000 km. Recently also quantum memory based on an ensemble of cold atoms and the process of electromagnetically induced transparency has been reported [24],[25],[26].

Future work on quantum memory based on the atomic ensemble approach should be concentrated on achieving efficient retrieval of the stored quantum state, improving the fidelity of storage and developing dedicated quantum error correction schemes necessary for achieving extra long storage times. Another promising direction is the exploration other types of atomic/solid state ensembles useful for storage applications; solid-state system such as those used for slow light experiments are potentially suitable for quantum memory and should be investigated.

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V. Offspring of CV research

V.1 CV quantum metrology

(quantum entanglement-enabled technologies, sensors)

V.1.a Squeezing-enhanced positioning accuracy

Measuring the pointing direction of a laser beam is one of the most direct, practical and sensitive applications of light. However, the measurement sensitivity of the pointing direction of a laser beam is ultimately limited by the quantum nature of light. To reduce this limit, spatially-squeezed states of light need to be utilized [1]. In particular, the enhancement of the positioning accuracy requires the signal coherent beam, which is usually in a Gaussian mode, to be mixed with a squeezed vacuum mode of the first-order Hermite-Gauss spatial profile. To give an example, using 3dB of squeezing in the correct spatial mode improves the positioning measurement by factor of sqrt(2). There are several quantum technologies allowing the production of squeezed states in Hermite-Gauss modes. These technologies are based either on mode converters allowing a transfer of squeezing from a Gaussian mode into higher-order modes, or on direct production of higher-order mode squeezing using nonlinear effects in optical fibers or optical parametric oscillators [2],[3]. The latter technique, the most efficient to date, showed that two 4dB squeezed orthogonal first order Hermite-Gauss modes can be produced using just one optical parametric oscillator. However, technologies based on optical waveguides and optical fibers are expected to be the most practical solutions for everyday applications.

V.1.b Spin squeezing, magnometer

To be completed.

V.2 Simulation of CV quantum systems

As a first step, Gaussian theories can be simulated using continuous variables. This approach is experimentally relatively simple and allows for observation of interesting properties of Hamiltonians [4],[5],[6]. However, as long as only Gaussian elements are involved, the simulation can be efficiently performed using a classical computer. Therefore non-linearities have to be added in the next step.

In principle, universal quantum simulation is possible using continuous variables [5], but special-purpose quantum simulators are also extremely useful and definitely a goal worth pursuing. Interesting systems such as N interacting particles in three dimensions are most naturally described by continuous variables. In such cases analogue simulations are advantageous and more adequate than a discrete treatment.

Promising directions for CV quantum simulation include the simulation of spin-boson problems [8], a continuous scheme for finding thermal (Gibbs) states [9] and the simulation of continuous quantum systems in quantum field theories. On the one hand, continuous variables in a continuous space are a natural choice for simulation of quantum fields. Continuous variables in discrete spaces on the other hand provide a link between quantum field theories and all discrete approaches [6].

The realization of more CV entangling gates, in particular non-linear gates, would not only represent an important step towards CV quantum computation; it would also open up new possibilities for quantum simulations, as many entangling operations combined with local rotations in a Trotter composition allow for simulation of time evolutions of interesting systems.

V.3 Detector technology

Detection is used for many different purposes in the quantum optical laboratory: Quantum states are characterized through detection, some quantum information processors are enabled through detection, the outcome of a quantum computation will eventually involve detection and quantum communication is inevitably linked with detectors. The quantum state is only properly detected if the detecting apparatus is not adding technical noise to the measurement outcomes; if the quantum signal is not much larger than the technical detector noise signal, the detector will not “collapse” the quantum state into an eigenstate of the measured observable. This means that quantum states will not be properly characterized, quantum information protocols will not be implemented unitarily and quantum communication cannot be made unconditionally secure.

The progress in experimental QIPC therefore relies crucially on the development of extremely low-noise detector technology, and, for some applications, also on the development of highly sensitive and broadband detectors. Sensitive detectors are of importance when the mesoscopic quantum state is detected directly without the use of a local oscillator, and broadband detectors are needed for high-speed quantum communication and for the implementation of real-time feedforward (or feedback) protocols [10],[11],[12],[13].

This detector technology can be used in all fields and industrial applications outside QIPC where these properties are important. The large signal-to-noise ratios achieved in CV detection setups can find applications in sensitive locking systems or measurement of faint signals in optical sidebands. The speed of optical metrology systems is ever increasing, e.g., to achieve higher throughput in production quality insurance. When optical power levels are limited, high-speed detectors with excellent noise performance are crucial. The development performed in CV-QIPC detectors can thus deliver valuable input for these applications.

The quantum efficiency of the PIN diode used in CV-QIPC detectors is also an important factor and can be enlarged by a careful material choice and efficient surface coating. Quantum efficiencies of up to 99% have been reported for both InGaAs PIN diodes and Silicon diodes. Apart from the advantage of this high quantum efficiency in the CV QIPC domain, it can be useful in spectroscopy and general low power light sensing applications. Already now, the development of some of the best commercially available InGaAs PIN diodes with high quantum efficiency was triggered by demand in measuring highly squeezed states of light.

V.4 Classical optical signal regeneration

Long-distance optical communication links require low-loss optical fibers, optical amplifiers and signal regeneration devices. The latter ones are currently using electronic signal regeneration techniques requiring the conversion from the optical to the electronic domain and after regeneration back to the optical level. As an alternative several groups attempt to develop all-optical signal regenerators hoping for high performance at low costs and, especially, at very high bit rates.

Methods of nonlinear optics developed to reduce quantum noise in squeezing experiments can also be applied for all-optical signal regeneration in communication systems [14]. In both cases the main requirement is to realize a device with a nonlinear transfer function which has a region of zero slope, a so-called “plateau”. If the signal amplitude is in the plateau region, its fluctuations will be suppressed and the signal with reduced amplitude noise will be obtained at the output. In telecom transmission systems, the same operation principle leads to 2R signal regeneration, which provides signal reshaping in addition to amplification [15]. Reshaping usually means that, on the one hand, the signal amplitude fluctuations are cancelled and, on the other hand, the weak and noisy background between the signal pulses is also suppressed. In many applications just one of the features is enough. But there are also limitations specific to an application field. For example, in the reduction of quantum noise neither common optical amplifiers can be used nor should the linear losses be too high. These restrictions do not apply to optical signal regeneration.

V.5 Hybrid systems, e.g., nanomechanical oscillators

All tools developed in CV-QIPC research are useful for the development of techniques and protocols with hybrid systems involving, e.g., nanomechanical oscillators. To be completed.

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