Preface

This book is a joint effort of a number of leading research groups actively developing the field of quantum information processing and communication (QIPC) with continuous variables. The term "continuous" refers to the fact that the description of quantum states within this approach is carried out in the phase space of canonical variables, x and p, which are indeed continuous variables over an infinite dimensional Hilbert space. Historically, the field of QIPC with continuous variables has dealt mostly with Gaussian states, such as coherent states, squeezed states, or Einstein-Podolsky-Rosen (EPR) two-mode entangled states. A powerful mathematical formalism for Gaussian states, which are completely described by only first and second order momenta, is presented in the first part of this book in the chapters by G. Adesso and F. Illuminati (entanglement properties of Gaussian states) and by J. Eisert and M. M. Wolf (Gaussian quantum channels). This is a useful tool in the study of entanglement properties of harmonic chains (see chapter by K. M. R. Audenaert *et al.*), as well as in the description of quantum key distribution based on coherent states (see chapter by F. Grosshans *et al.*). A more exotic topic involving Gaussian states is covered in the chapter by O. Krüger and R. F. Werner (Gaussian quantum cellular automata).

Gaussian operations on Gaussian states alone do not allow for the purification and distillation of continuous-variable entanglement, features which are critical for error corrections in QIPC, so that the recourse to non-Gaussian operations is necessary (see chapter by J. Fiurášek *et al.*). Non-Gaussian operations are also crucial in order to build loophole-free Bell tests that rely on homodyne detection (see chapter by R. García-Patrón). Interestingly, the continuous-variable formalism is also appropriate for the analysis of non-Gaussian states, such as Fock states, qubit (quantum bit) states, and coherent superposition (Schrödinger cat) states. Indeed, the Wigner function over an infinite dimensional Hilbert space provides the most complete description of any state, including a discrete variable, qubit state. The Hilbert space may be spanned by the Fock state basis in the case of a single field mode, or, in the case of single photons, by the spectral mode functions. The characterization of such non-Gaussian states by homodyne tomography is reviewed in the chapter by G. M. D'Ariano *et al.* Then, recent theoretical developments in the generation of particular non-Gaussian states (Schrödinger cat states) are presented in the chapter by H. Jeong and T. C. Ralph.

Continuous variables have played a particularly important role in QIPC with light, due to the highly efficient and well experimentally developed method of "homodyne detection", which provides a direct access to the canonical variables of light. This area of "optical continuous variables" is covered in the second part of this book. Here, the variables x and p are the two quadrature phase operators associated with the sine and cosine components of the electromagnetic field. By mixing the quantum light field under investigation with a strong classical "local oscillator" light on a beam splitter, the variables x and p can readily be observed, and hence a complete description of the quantum field is obtained. If one takes into account the polarization of light as an additional degree of freedom, the Stokes operators have to be introduced and the notions of polarization squeezing and polarization entanglement arise, as described in the chapter by N. Korolkova.

Several recent experiments with continuous variables of light are presented in this part of the book. For example, the chapters by J. Laurat *et al.*, O. Glöckl *et al.*, and V. Josse *et al.* present the generation of EPR entangled light via the optical nonlinearities provided by solid state materials and cold atoms. Some other chapters present several applications of optical continuous variables to QIPC protocols, such as quantum teleportation by N. Takei *et al.*, quantum state sharing by T. Tyc *et al.*, and quantum cloning by U. L. Andersen *et al.* Applications of continuous-variable squeezing to ultra-precise measurements are covered in the chapters by C. Fabre *et al.* (quantum imaging) and by R. Schnabel (towards squeezing-enhanced gravitational wave interferometers). For single-photon states, the concept of canonical continuous variables can be transferred to other observables, e.g. the position x and wave vector k, as shown in the chapter by L. Zhang *et al.*

The non-Gaussian operations such as photon counting combined with the continuous-variable homodyne-based analysis of the light conditioned on photon counting take QIPC with optical continuous variables into a new domain. This domain, where the purification of entanglement and error correction is, in principle, possible, is explored experimentally in the chapters by J. Wenger *et al.* (photon subtracted squeezed states) and by

A. I. Lvovsky and M. G. Raymer (single-photon Fock states). The latter chapter reports on the progress in experimental quantum tomography and state reconstruction.

Another avenue in QIPC with continuous variables has opened up when it was realized that multi-atomic ensembles can well serve as efficient storage and processing units for quantum information. The third part of this book is devoted to the development and application of this approach based on "atomic continuous variables". The quantum interface between light pulses carrying quantum information and atomic processors has become an important ingredient in QIPC, as some of the most spectacular recent developments of the light-atoms quantum interface have been achieved with atomic ensembles. The continuous-variable approach to atomic states has proven to be very competitive compared to the historically first single atom and cavity QED approach.

The theory of quantum non-demolition measurement on light transmitted through atoms, quantum feedback, and multi-pass interaction of light with atoms, is presented in the chapters by L. B. Madsen and K. Mølmer and by R. van Handel *et al.* Experiments on spin squeezing of atoms are described in the chapter by J. M. Geremia, while the theory and experiments of EPR entanglement of distant atomic objects and quantum memory for light are presented in the chapter by K. Hammerer *et al.* Atomic ensembles can also serve as sources of qubit-type entanglement. In this case, a single qubit state is distributed over the entire multi-atomic ensemble, providing thus a conceptual bridge between a discrete computational variable and a continuous (or collective) variable used as its physical implementation. The work towards the implementation of a promising proposal for the generation of such type of entanglement conditioned on photon detection (the Duan-Lukin-Cirac-Zoller protocol) is presented in the chapter by C. W. Chou *et al.* Interestingly, such an analysis of qubits in the continuous-variable language makes the old sharp boundary between continuous and discrete variables softer. Finally, the theory of decoherence suppression in quantum memories for photons is discussed in the chapter by M. Fleischhauer and C. Mewes.

In summary, this book is aimed at providing a comprehensive review of the main recent progresses in continuous-variable quantum information processing and communication, a field which has been rapidly developing both theoretically and experimentally over the last five years. It was originally intended to review the main advances that had resulted from the project "Quantum Information with Continuous Variables" (QUICOV) funded by the European Commission from 2000 to 2003. However, given the unexpected pace at which new paradigms and applications continued to appear, it soon became clear that this objective had become too restrictive. Instead, this book evolved into a compilation of the even more recent achievements that were reported in the series of workshops especially devoted to continuous-variable QIPC that took place in Brussels (2002), Aix-en-Provence (2003), Veilbronn (2004), and Prague (2005). Yet, the picture would not have been complete without the contributions of several additional world experts, which have rendered this book fairly exhaustive. We are confident that the various directions explored in the 27 chapters of this book will form a useful basis in order to approach continuous-variable QIPC. This is, however, probably not the end of the story, and we expect that future developments in this field will open new horizons in quantum state engineering, quantum computing and communication.

We warmly thank Gerlinde Gardavsky for her careful work on preparing the lay-out, correcting and proof-reading this book.

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