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High Dimensional Entangled Systems

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Summary of the project activities (October 1, 2008-January 31, 2012)

Entanglement and quantum correlations are the fundamental tools for building protocols of Quantum Information Processing and Communication (QIPC). These fields passed in the last years the proof-of-concept stage, asking now for real-world implementations.

In this context, light plays a fundamental role as the natural carrier of information over large distances and between logic elements within a processor. The standard approach of quantum optics that deals with single or two-mode systems is inadequate in view of practical implementations of QIPC, not only because it is unrealistic, but also because it creates a bottleneck in the information capacity of the quantum channels.

The project HIDEAS aims at a breakthrough in the information capacity of quantum communication, by exploiting the intrinsic multivariate and multi-modal character of the radiation field. The long term vision underlying our project is that of a **broadband quantum communication**, where all the physical properties of the photons are utilized to store information.

The general objectives are to study, on the one hand, how to produce in a controlled way quantum entanglement of light in high dimensional and multimodal spaces, and, on the other hand, how to create multimode quantum interfaces between light and matter so that quantum states of light can be stored and processed in long-lived matter degrees of freedom.

From a different perspective, our research aims at contributing to the field of metrology, a domain where multimode aspects have been introduced with great success ("frequency combs"), and quantum noise tailoring demonstrated a powerful tool to increase the sensitivity of high-precision measurements ("quantum metrology").

The path to reach such general objectives proceeds along five research lines (work packages, WPs) that address both the light (WP1-WP4) and the matter (WP5) aspects, spanning the continuous variable (WP1,WP2) and the photon-pair (WP3,WP4) regimes and encompassing temporal (WP1), spatial (WP2,WP3) and spatio-temporal (WP4) degrees of freedom.

An important tool for broadband information technologies is to convey information by means of the temporal variation of a light beam confined in a single spatial mode. In this context, optical frequency combs are perfect tools for high precision metrological applications. The extension of their extraordinary properties to the quantum domain, which is the aim of our first work package **WP1**, *High-D temporal entanglement: quantum frequency combs,* promises significant progress not only in quantum metrology and parameter estimation, but also in quantum computation with continuous variables. Here, one of the main challenges, for example in cluster state computation, is the generation of highly multimode non-classical states of light, and the scalability of this generation. The theoretical investigations in WP1 have completely characterized the quantum properties of light generated by a Synchronously Pumped Optical Parametric Oscillators (SPOPO), i.e an Optical Parametric Oscillator whose cavity length is the same as the femtosecond laser cavity pumping it. They have shown that the great complexity of the highly multimodal intracavity parametric interaction can be described by a substantially reduced number of *supermodes* which are the eigenmodes of the nonlinear interaction. Squeezing, i.e. reduced quantum fluctuations in field quadratures, was predicted to occur in supermodes [*Patera2010a*]. The studies pursued in the project have shown the possibility of creating quantum entanglement between different frequency components, between different time windows, and between pulses of different shapes, generated by a SPOPO both below and above its threshold [*Averchenko2011a*, *Averchenko2011b*] . They have also shown that it is possible to produce cluster states that are useful for quantum computation by appropriately shaping the nonlinear interaction creating the non-classical resource [*Patera2012*].. In particular choosing the temporal shape of the pump permits to control the number of entangled modes, as well as the distribution of their quantum correlations, thus permitting a highly flexible generation of arbitrary multimode Gaussian states. Giant noise amplification of pulses has been predicted in singly resonant SPOPOs via non-orthogonal properties of the field operators, leading to the possibility of macroscopic quantum entanglement in [*Cuozzo2011],* [*Cuozzo2012*]. Finally, the work in WP1 addressed the important issue of storing temporally entangled light in broadband quantum memories, showing [*Zhan2012*] that frequency combs can be actually stored and retrieved in the lambda pump-probe Raman-like configuration.

The corresponding experiments are still at a preliminary stage, because almost nothing had been done in this domain before the beginning of the present project. The experimental SPOPO setup developed at UPMC, used a novel technique to synchronize optical cavities to frequency combs, which is now patented [*Pinel2010*]. The SPOPO works with a very low threshold (16mW) and has been shown to generate intensity squeezing below its threshold with typically -1. dB of squeezing currently achieved. An important result within this project is the demonstration of non-classical multimode frequency comb, displaying quantum correlations between the different parts of the spectrum[*Pinel2012a*]. By diagonalizing the noise covariance matrix, the profile of 4 independent supermodes was deduced from experimental data, among which two show intensity squeezing and one enhanced fluctuations. Towards the end of the project a new setup for the homodyne detection of squeezing/entanglement in the quadratures of supermodes have been built, which is likely to enable in the next future to demonstrate stronger quantum effects, involving a larger number of modes.

The reduction of quantum fluctuations in frequency combs can be used in quantum metrology to measure ultra-small time delays, in order e.g. to improve the synchronization of remote clocks. WP1 investigated the interest of using Gaussian non-classical states for time measurements. A fundamental theoretical achievement (which is in common with the next workpackage) here is the demonstration that in order to optimize the accuracy in the estimation of any parameter (including a time delay) with multimode non-classical light, the best way is to concentrate all the squeezing available in a single well defined light mode, called the detection mode [*Pinel2012*]. An experimental setup to measure ultra-small time delays has been built and optimized. UPMC worked on the two key points which will hopefully enable them to realize the measurement with quantum enhanced sensitivity: a very low noise frequency comb source and an efficient pulse shaping technique.

As an alternative to temporal modes, information can be encoded in the transverse light distribution of an optical beam, i.e. in *images,* which are privileged means to convey a great deal of information in parallel. Our second workpackage **WP2,** *High-D spatial entanglement (continuous variables),* investigates at the quantum level i) the best ways of generating spatially entangled multimode light, which is the highly-entangled quantum resource necessary for spatially broadband quantum information ii) the way to use these multimode quantum resources to improve various functions of spatial information processing (e.g, to enhance the sensitivity in image processing, or in the detection of ultra-small 3D displacements and rotations), and iii) the properties of spatially multimode light suitable to be interfaced with multimode quantum memories.

At year two of the project several experimental achievements in the generation of spatially entangled light were already established, which allowed a critical comparison of the different approaches pursued:

- The first approach is based on the use of nonlinear optical processes in highly degenerate cavities, which directly emit intrinsically multimode light . UPMC set up and optimized a self-imaging optical parametric oscillator, characterized by a self-imaging cavity that resonates simultaneously for all the transverse modes at the same frequency. The multimode capabilities of the device have been assessed showing for the first time frequency doubling of images of arbitrary shapes[*Chalopin2010a*]. Multimode squeezing effects on three orthogonal transverse modes have been measured [*Chalopin2011*], in agreement with the theoretical prediction [*Lopez2009*] when experimental imperfections are taken into account. Moreover, it was shown that the oscillation threshold can be crossed while keeping multimode non-classical results [*Chalopin2010b*] .
- A second approach is based on travelling-wave parametric processes (without the cavity), which naturally generate a huge number of modes. In this context COMO demonstrated sub-shot noise spatial correlations in

hundreds of modes, without any background correction [*Brida2009*], which opened the concrete possibility of imaging with quantum enhanced a sensitivity.

-The last approach is based on entanglement synthesis from several individual modes. In year 2 ARC, in collaboration with UPMC, implemented an experiment to generate and directly detect for the first time entanglement between two orthogonal transverse modes co-propagating in a light beam.. EPR-like entanglement was demonstrated and the related work is published in Nature photonics [*Janousek2009*]. This last technique proved to be the most robust and versatile in short term applications, because of the high level of squeezing achieved, which cannot be reached by the other two methods within current technologies.

During year 2 un important device was developed, namely the *Universal Programmable Mode Converter* (*UPMC*), based on the use of spatial light modulator to convert the spatial shape of one mode to another [*Morizur2010a*,*b*]. Mode conversion can be done while preserving the non-classical features, which is of paramount importance for multimode spatial light manipulation.

Building on these results, in the last year of the project ARC, in collaboration with UPMC, has turned its multi-squeezed beams machine into a programmable cluster state source. The underlying principle is that cluster state generation from single squeezers is a unitary operation equivalent to a basis change. This is performed via optical networks in usual cluster state implementation; it can be replaced by the series of unitary image transformation (*UPMC* device) and homodyne detection with a mode shaped local oscillator and multipixel detectors. In this way it was possible to demonstrate from 2 up to 8-mode entanglement, the results being submitted to Nature Photonics [*Armstrong2012*]. Intrinsically robust and scalable, this strategy represents a promising route towards quantum information processing, and is the major outcome of this whole research line.

Spatially entangled light can be employed in ultra sensitive multi-parameter position estimators: as indicated by the theoretical result in [*Pinel2012a*], this task relies on the ability to control which mode carries which quantum property. ARC and UPMC have proposed an experimental implementation [*Morizur2012*], based on the *UPMC* device in order to generate squeezing exactly into the mode carrying the information on the parameter to be measured. This idea has been studied in the practical case of the detection of the small lateral movements of a glass filament, with a quantum enhancement expected realistically between 70% -80% .

On the theoretical side, USTL performed a study on the ability to generate N-partite entanglement using N symmetrically-tilted plane waves for pumping a parametric medium[*Daems2010*]. UPMC produced a detailed review about the application of the powerful tools of symplectic invariants to multimode light [*Leroyer 2010*], while USTL extended the symplectic theory in order to keep into account the non trivial space-time structure of multimode entanglement [*Patera2010b*]. UPMC and USTL demonstrated the possibility of tailoring the spatial entanglement of the modes generated an Optical Parametric Oscillator [*Patera2012*] by shaping the pump spatial profile. Like in the temporal case, spatial pump shaping provides a simple way to control the properties of the generated multimode state, and for example cluster states of Gauss-Laguerre modes can be generated.

With the purpose of studying the problem of interfacing spatially multimode light with quantum memories USP and UPMC demonstrated that a large number of transverse modes can be stored independently [*Golubeva2011a*], while UKBH solved the full three dimensional problem of light storage in an ensemble and investigated the performance of the memory for storing spatial correlations [*Zeuthen2011,Grodecka-Grad2011*].

Our **WP3**, *High-D spatial entanglement (photon-pairs)* shares with WP2 the interest towards entanglement in the spatial degrees of freedom, but here the focus is on the two-photon entanglement produced by spontaneous parametric down-conversion (PDC). The idea is to increase the quantum bandwidth of photonic communication channels by feeding the channels with highly spatially entangled photon pairs, therefore allowing communication with a larger alphabet (qudits) compared to the usual binary alphabet (qubits) allowed by the polarization. The main objective is to demonstrate experimentally high-D entanglement of such photon-pairs (aiming at $D \approx 50$), and to establish its usefulness for quantum communication**.**

The work performed within this project has seen a number of relevant experimental achievements:

-The UL setup is based on the idea of projecting the two-photon state on a superposition of the orbital angular momentum (OAM) eigenstates, by using an angular phase plate coupled to a single-photon detector. As a crucial step towards high-D spatial entanglement, the first year focused on the fabrication of the optimum phase plates. The UL team compared several technologies, and found that photolithography lead to superior phase plates. Angular projectors based upon these phase plates were used to study high-D two-photon entanglement, and in particular to test the robustness of OAM entanglement towards propagation in free space[*Pors2011a*]. The limits to high-dimensional angular entanglement have been explored; these are determined both by the Schmidt number of the PDC set-up and by the azimuthal/radial geometry of the phase-plate projectors. By optimizing the PDC setup, and in particular by properly choosing the phase matching conditions inside the nonlinear crystal, UL is now able to report a measured Schmidt dimensionality on the order 30-45 [*DiLorenzo2010, Pors2011b*]. In joint work between UL and USTRATH spatial light modulators have been used to encode the Leiden approach for sector phase plates of high dimensionality. Using this approach, orbital angular momentum spiral bandwidths of k≈50 have been measured. Moreover, the UL team demonstrated for the first time the transport of spatially entangled qudits with D=3 (i.e. qutrits) in a hollow-core photonic crystal fiber [*Loeffler2011*]. This represents important progress towards practical applications of OAM entangled photons in quantum communications.

-The USTRAT setup is based on the use of spatial light modulators for the measurement of the spatial modes of the photons. In year one their PDC setup was upgraded with a mode-locked pump laser, and the demonstration of the efficacy of a silicon photon avalanche diode (SPAD) working at 710 nm. The setup was used to demonstrate a non-local violation of a Bell-type inequality for the orbital angular momentum states of light. In terms of the dimensionality of entanglement, full entanglement has been observed up to a modal index ℓ= 23 [*Leach2009*]. Within a ghost imaging setup [*Jack2009*], edge enhancement in imaging was demonstrated as a direct consequence of the quantum correlations in the orbital angular momentum of photons. Also in this case, a violation of a Bell-type inequality for an OAM subspace was shown. In the second year of the project a true highlight achievement was the demonstration, for the first time to our knowledge, of EPR correlations between down-converted photon pairs in terms of angular position and angular momentum. Correlations an order of magnitude stronger than those allowed by the uncertainty principle to non-entangled particles have been measured [*Leach2010*]. This result establishes that angular position and angular momentum are suitable variables for applications in quantum information processing, notably in protocols for quantum key distribution. As a final for the project, the USTRAT team developed a new approach to measuring the spatial position of a single photon. Using optical fibres of different length, all connected to a single detector allow the use of the high timing precision of avalanche photodetectors to spatially locate the photon. Two 8-element detector arrays were used to measure the full-field quantum correlations in position, linear momentum and intermediate bases of PDC photon pairs [*Leach2012*], with a demonstration of an EPR-like inequality for position and momentum.

Our fourth research line, **WP4**, *High-D spatio-temporal entanglement: quantum X-waves* focuses again on the entanglement of PDC photon-pairs, and addresses the quite novel issue of the non factorability in space and time of the biphoton entanglement. The idea comes from nonlinear optics, where wave-packets characterized by a X-shaped spatio-temporale profile (X-waves) are known to emerge in non-linear media. The objective of WP4 is to demonstrate the microscopic counterpart of these phenomena, and to assess the possibility of tailoring the temporal entanglement of photon pairs by controlling their spatial degrees of freedom and viceversa. Being nowadays PDC the most efficient and common source of entangled photons, the subject controlling the spatio-temporal correlation/coherence properties of biphotons is of paramount importance in modern QIPC technologies.

Since WP4 addressed a completely novel issue (with few exceptions, PDC was described in the literature with either purely spatial or purely temporal models), a large part of the work was of exploratory nature. A consistent theoretical effort demonstrated and characterized the geometry in the spatio-temporal domain of the biphoton state generated by various types of parametric processes. Our analyses [*Gatti2009, Caspani2010, Brambilla2010, Gatti2012a*] evidenced that close to collinear phase matching, the spatio-temporal biphoton correlation assumes a characteristic biconical shape, which looks as an X in any plane containing time and a spatial coordinate, a feature that we called *X-entanglement*. The non factorability of the correlation in space and time indicated us the possibility of manipulating the temporal bandwidth of the biphoton entanglement by acting on their spatial degrees of freedom, and in particular of achieving an ultranarrow relative temporal localizations of biphotons, in the femtosecond range, when their near-field positions are resolved. This result is unexpected, since in typical measurement schemes the correlation time of biphotons is determined by the dispersion broadening in the crystal, while we show that, by localizing spatially the photons, dispersion is cancelled by diffraction, so that the full detected bandwidth of PDC (extending to the optical frequency range) contributes to a temporally localized correlation peak.

The work in year 2 solved the crucial issue of identifying a measurement scheme able to demonstrate the main features of X-entanglement, and demonstrating the feasibility of the proposed setup. We concentrated on a setup where the spatio-temporal correlation of twin beams generated in a first nonlinear crystal is probed by using the inverse process of sum frequency generation (SFG) in a second crystal that acts as an ultrafast correlator [*Brambilla2011*]. Following these outcomes, a set up was assembled in COMO [*Jedrkiewicz2011*], which enabled the unambiguous experimental evidence of the X-geometry of the biphoton correlation. We have been able to demonstrate the ultranarrow (6 fs full with half maximum) temporal correlation of twin beams predicted by theory, the narrowest to our knowledge demonstrated in experiments using SFG as a probe for PDC. Moreover, the experiment shows the sensitivity of the temporal correlation with respect to manipulation of spatial degrees of freedom, in particular a remarkable broadening of the *temporal* correlation caused by *spatial* filtering or *spatial* diffraction in free space of twin beams [*Jedrkiewicz2012a*] , which gives clear evidence of the claimed non-factorability of the state. Finally, by controlling independently a temporal delay and a transverse spatial translation between the twin beams before the up-converting crystal, we could give full evidence of the characteristic X-shape of the correlation in the spatio-temporal domain [*Jedrkiewicz2012b*]. The theoretical and experimental characterization of X-entanglement are novel achievements that can be completely ascribed to the HIDEAS project**.**

On the purely theoretical side, a fruitful collaboration between COMO and USTL permitted to have a deep insight into the problem of quantifying the degree of entanglement of twin photons in the full spatio-temporal domain, which had never been addresses in the previous literature. By performing calculations of the spatio-temporal Schmidt number [*Gatti2012b, Horoshko2012a*] and Schmidt modes [*Horoshko2012b*] of X-entangled biphotons, we could conclude that also in this case consideration of both spatial and temporal degrees of freedom of twin photon is essential in order to correctly characterize their entanglement.

A quantum communication network is impossible without a quantum interface between light – the carrier of information – and matter – the storage medium for quantum information. Up to now, the work on light-atoms interfaces has been mostly limited to the case of a single spatial mode of light and a single spatial mode of atomic ensembles. Our **WP5**, *High-D entanglement of light and matter: quantum holograms* aims to extend this approach to multi-mode light-atom quantum interfaces. The main objective is to investigate multi-mode quantum memories for light based on spatially extended atomic ensembles, which we call quantum holograms, with the ultimate goal of an experimental demonstration of the extended spatial memory capacity of the quantum hologram, compared to a classical hologram.

To lay the foundation of the work in WP5 the theoretical investigations started with the development and critical comparison of various schemes for multi-mode quantum memories, including a thin quantum hologram with feedback [*Vasilyev2009*], a quantum volume hologram [*Vasilyev2010*], based on counter-propagating quantum signal wave and strong classical reference wave, and protocols based on the Faraday interaction or on Λ-type atomic level structures [*Hammerer2010, Golubeva2011a*]. These studies, done in a joint effort of the USP, UPMC and UKBH partners, enabled us to understand how the various memory protocols work in an idealized limit, where the density of the storage medium is constant transverse to the propagation direction of light. In the second year we moved away from the ideal limit and the question of the memory efficiency in the presence of fluctuations and losses has been analyzed in 3-D models for different interaction schemes [*Golubeva2011a, Golubeva2011b, Vasiliyev2011a, Zeuthen2011*]. In the last year these analyses have been used to reach the final objective of the theoretical research in Wp5, with the evaluation of the full information capacity of multimode quantum memories [*Grodecka-Grad2011,Vasilyev2011b,Vasilyev2011c*]. The results obtained thereby enable us to have a clear understanding of the potential applications and limitations of multimode quantum memories based on spatially extended atomic ensembles. Interestingly, our results indicate that the memory capacity that one achieves by considering the full spatial structure of the ensemble is much higher than naively expected from by extrapolating from the one-dimensional results [*Grodecka-Grad2011*], thus identifying the spatial degree of freedom as a strong resource for multimode quantum memories.

An experimental highlight result has been achieved in the 2^{nd} project year with the demonstration of a two-mode quantum memory [*Jensen2011*]. In a setup with room-temperature Cesium atoms, the write operation into a quantum memory for entangled two-mode states of light has been demonstrated. Storage of the quantum noise of two entangled light modes differing in frequency and interacting with two separate vapour cell is achieved in a configuration complementary to a spatial hologram – here different frequency components of single spatial mode light-field are stored in orthogonal spatial modes of atomic spin coherence.

Storage of quantum information in many spatial modes poses several new challenges to experiments. The modes of the storage medium need to be kept orthogonal over the desired storage time. Furthermore, write and retrieval operations need to be performed with independent control for individual modes. To meet these challenges the focus of the experimental work has been on cold atomic ensembles as storage media, because here the motional dephasing is inherently slow, and on the development of the experimental tools to characterize coupling efficiency, noise properties and decoherence for many modes in parallel. At UPMC and UKBH three complementary cold atom setups with Caesium and Rubidium atoms have been characterized and their suitability for multimode storage evaluated. Decoherence of squeezed, genuinely nonclassical, spin states have been characterized using an atomic clock protocol on the Caesium hyperfine transition with cold dipole trapped atoms [*Louchet-Chauvet*2010]. The achievable coupling strength for many modes has been investigated using spatially resolved Faraday imaging with ultracold Rubidium atomic samples [*Kaminski2010*]. A strong decoherence mechanism for collective motional states due to light assisted collisions in high density ultracold samples has been identified and quantified by measuring the threshold behavior of superradiant scattering [*Kampel2012b]*. In the last project period single mode storage protocols have been successfully applied in two setups at UPMC and UKBH [*Giner2012, Kampel2012a*]. A spatially resolved homodyne detection scheme allowing for shot-noise limited measurements on multiple retrieved light modes has been developed at UKBH and used to characterize storage efficiency and excess noise locally. At the end of the project all tools are available to demonstrate few mode storage and positive experimental results are expected in the near future.

Publications, patents

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