3.1 Publishable summary

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MALICIA aims at the creation of robust and scalable quantum interfaces between different platforms for the implementation of Quantum Technologies. We will focus on interfacing interaction or measurement induced quantum resources in atomic matter to light fields, based on less demanding alternatives to cavity-enhanced interaction of light with single ultracold atoms. For some applications we even plan to use thermal atoms which allow for a further reduction in the experimental complexity. To this end we want to push the evolution of Quantum Technologies further towards technologically scalable quantum devices. We will realize quantum devices and interfaces based on Rydberg blockaded gases, quantum gases and room temperature gases in microfabricated structures as well as the full theoretical framework for their description. The new expertise emerging from our project will provide a platform for progress in Information and Communication Technology (ICT) towards real-world deployment of quantum repeaters for long-distance quantum communication.

In classical communication information is transferred encoded in pulses of light. The pulses are detected by photodetectors, transformed into electrical current pulses, amplified by electronics, and sent to computers, phones, etc. This transformation of light into electrical signals forms a classical light-matter interface. In quantum information processing, this simple approach is inadequate as it destroys the quantum aspect. Quantum communication requires a coherent storage interface – quantum repeaters.

In the next 5-10 years we should see fibre optic systems that can beat the direct-transmission distance limitation of around 300-400 km. Initially, quantum repeaters that can function over 1-10 km will provide the building blocks for longer transmission systems – it is these building blocks that provide a scalable route towards pan-European and even global scale quantum communication. These distances will obviously need to be extended further, but not necessarily by much. We note that classical communication links are of the order of 50-100 km between amplification stages. The important aspect for quantum repeaters is the scaling of multiple quantum repeater links. Scalable quantum repeater systems will ensure that the concatenation of multiple links will extend quantum communication distances beyond this fundamental (loss-based) limit. Effort in the next few years should be focused on engineering the sources, interfaces and detectors specifically adapted to long distance transmission and working in unison – long coherence lengths, and high fidelity Bell-State measurements and work towards input/output coupling of photons to Quantum Memories etc.

Project MALICIA tackles, in a combined and integrated effort all the different aspects needed fo a repeater i.e.: extending memory capabilities to single photon/qubit storage in diverse media; exploring hybrid approaches; develop probabilistic repeater schemes, integrated using atoms on chip technology; integrated solutions or circuits that connect multiple elements: source; detector; interface; incorporate deterministic strategies for sources, storage and entanglement swapping.

The Project is articulated in five work packages (WP's). WP1 is dedicated to developing the novel promising techniques based on *Rydberg blockaded ensembles* as sources of non-classical light or as Quantum Repeaters; WP2 makes use of *optically dense room temperature atomic samples* to store, process and retrieve non-classical information; WP3 uses *quantum gases* to transfer massive entanglement between atomic and light states; WP4 provides the necessary framework to complement and orchestrate the development along the different lines. The first three WPs have mainly an experimental character while the fourth one will have a strong theoretical lead. Finally WP5 is devoted to managing the project.

MALICIA project has completed its first year with many interesting developments along the foreseen lines in particular with the experimental platforms achieving the desired goals to push forward the project objectives and with the theoretical groups fine tuning their instruments on the different experiments. Our partner groups have been fertilising each other considerably, through close collaborations; these, we are convinced, are what is needed to make significant progress in the use of quantum resources to be exploited in future quantum information devices.
In the second year the project has continued its steady progress with many interesting results that have appeared in various international publications.

WP1: Rydberg blockaded ensembles

The three teams USTUTT, UULM and UA have closely worked together during the second year reaching all goals as proposed within in the given time schedule. USTUTT group have implemented important building blocks towards a room temperature single photon source. First of all the experimental observation of the von-der-Waals interaction in a thermal gas at a GHz bandwidth. This result has shown, that also the blockade effect has to be present for the same experimental parameters. USTUTT has already set up a four-wave mixing (4WM) experiment with pulsed laser sources and single photon detectors, where the excitation volume has now to be scaled down to a single blockade volume.
For this task USTUTT has considerably benefitted from the theoretical work done in UA and UULM, where it was proved that only the Doppler-class contributing to the 4WM has to be smaller than the full Doppler-width. If not, one would lose in fidelity due to the spatial motion of the fast atoms, which quickly leads to a dephasing of the otherwise directed emission.
The UULM group has focused on numerical simulations of the strongly interacting system and optimized the exciting pulse sequence for an optimal fidelity of directional single photons. The UA group has been studying similar systems, but with a focus on analytical as well numerical studies on the time evolution of the system. In particular studies were dedicated to the shaping of the outgoing light pulse such that it would be optimally absorbed by another ensemble of atoms. Both UULM and UA studies has shown that the thermal motion leads to unwanted dephasing but this can be kept under control with the suitable experimental strategy.

WP2: Optically thick samples

In close collaboration, MPG and UCPH have made a deeper study of the protocol for the generation of entanglement between two macroscopic room-temperature atomic ensembles through dissipation. The original experiment was able to achieve entangled states available during a time interval of 1 h. In the present study, we provide further-reaching experimental data and an extension of the theory previously available, in particular proving that the combination of the purely dissipative mechanism with continuous measurements can give rise to a substantial improvement of the entanglement generated.
On the other hand, LUH has explored decoherence sources in room temperature atomic gases, a vital study prior to the complete analysis of the limitations present in the dissipative generation of entanglement mentioned in the previous paragraph. In particular, a comprehensive model of quantum noise due to spontaneous emission was developed. This model relates the effective damping rates and Langevin forces for atomic and light modes to the microscopic parameters of the

light-matter interaction, and eventually to some intrinsic atomic properties (such as the relevant Clebsch-Gordan coefficients of the atomic species).
Note that these two studies were published in the special issue on quantum memories of the Journal of Physics B: Atomic, Molecular, and Optical Physics.
LUH has further investigated protocols for steady state entanglement generation by means of Gaussian interactions and operations. We generalized the protocol for the creation of entanglement by dissipation to an arbitrary Gaussian interaction between the atomic ensembles and the light field. Taking into account also homodyne detection of light, and using the formalism of quantum stochastic master equations, we determined the optimal Gaussian protocols for the generation of stationary entanglement of atomic ensembles.
UCPH has developed a quantum limited radio frequency magnetometer. The measured noise is a combination of photon shot noise, back-action noise from the probe and spin noise associated with the quantum state of the orientated atoms (Deliverable 2.4).
The UCPH is currently working on implementing a pulsed measurement scheme together with an optical cavity, which will increase the coherence lifetime and the light-atom coupling.
In another line of work, UCPH has also experimentally demonstrated the first deterministic cv teleportation between two macroscopic atomic ensembles. This experiment is based on the teleportation protocol devised in Deliverable 2.2. The experience and techniques developed for the macrocells should be readily transferred to microcells.

WP3: Quantum gases

LENS has experimentally evaluated the limits of its own Atom Chip based ultracold rubidium sample as a quantum storage device. Optical depths and attainable optical delays have been measured and the maximum storage time has been foreseen for a thermal sample above quantum degeneracy. The expected times are between 1 and 3 μs depending on the chosen parameters, therefore much lower than those attainable in the thermal and Rydberg blockaded samples.
On the other hand, the system lends itself to a different set of observations and MPG has proposed a practical method to measure quantum dynamical correlations using QND-type interactions and quantum memories. The scheme makes use of the Faraday interaction for repeated QND read-out of system observables and intermediate coherent storage in a quantum memory. The scheme provides direct access to spectral and dynamical properties of the system and may open a way for quantum-conditional feedback.
Much more success has been achieved in the atomic interferometric scheme devised for the measurement of quantum coherences in the sample. During the first year we had developed an original scheme for multi-state atomic interferometry. We have applied the interferometer for the detection of the phase written on the atomic sample by two optical beams. Furthermore, in close collaboration with UULM we are applying CRAB optimization methods for the initialization and readout of the atomic interferometer in order to maximize its sensitivity.
In a parallel development LENS has also been starting to experiment with single photon sources suitable for coupling to the Atom Chip.

WP4: Quantum Interfaces

For this WP all the MALICIA partners have collaborated. In particular the description of propagation of light in a medium under four wave mixing conditions based on the optical nonlinearity provided through the Rydberg-blockade effect was developed by UULM and AU allowing the development of a theoretical model to be used by other consortium partners (D4.2).
Furthermore AU has continued efforts to establish analytical and numerical theory for atom light Interfaces while LUH studied dynamics in non-linear atomic media showing, in particular, that entanglement in the form of Bell states of collective atomic excitations can be generated in steady state via a continuous homodyne Bell measurement.
At the same time MPG investigated dissipative quantum repeater protocols and rates at which they can yield highly entangled long-range qubits as UULM performed numerical simulations modeling light-matter interactions in Rydberg blockaded ensembles.

On a more experimental side USTUTT worked on overcoming technical problems on the way to the single photon source based on Rydberg blockade, in particular, how to address exactly one of the blocked volumes in the vapor cell. LENS has been providing data for the optical memory implementation on ultracold atoms while at the same time providing experimental evidence of the successful application of CRAB methodology for the optimization of the dynamics of cold atoms in an optical lattice.