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.

WP1: Rydberg blockaded ensembles

In this first year our partners in USTUTT followed a twofold approach, one based on Rubidium atoms and the other on Cesium atoms. For Rubidium we can rely on our broad experience on Rydberg excitation in thermal vapours and here we have succeeded now to demonstrate four wave mixing involving Rydberg states including extended numerical simulations. In another project we have been able to observe the coherent dynamics of a pulsed Rydberg excitation with sub-nanosecond resolution published in Physical Review Letters. In the case of Cesium we have purchased, installed and tested a laser system for an inverted excitation scheme into Rydberg states. Here we have observed electromagnetically induced transparency accompanied by enhanced absorption peaks, caused by couplings to additional electronic states. A detailed experimental and theoretical analysis of the corresponding multi-level system is being currently developed. Besides this we have installed an ultrafast Pockels cell, which will serve in combination with a fiber amplifier as a high power source for pulsed excitations in Cesium. Finally we were able to produce electrically contacted vapour cells based on the technology of liquid crystal displays, which are vacuum tight and compatible with rubidium vapours.
The demonstration of four-wave mixing involving Rydberg states is a key result for the development of a single photon source based on the blockade effect. From our experiments we have learned that the excited state population in a steady state configuration is quite small and we do have to switch to a pulsed excitation to enter the regime of strong interactions. Besides this we have to reduce the size of the excitation volume to the size of a single superatom to receive a real single photon source. Until now we do not have fundamental concerns on the feasibility of a thermal vapour single photon source and the combination of the four wave mixing scheme with a pulsed excitation in Cesium vapours will be the best direction to pursue this project. A single photon source based on Alkali vapours will be robust, fully integrable and can be produced with standard technologies used in industry leading to a cheap, microscopic and stable device.

WP2: Optically thick samples

Our partners in MPQ proposed a feasible scheme for quantum teleportation between two atomic ensembles. The new procedure uses temporal modulation of coupling and read-out and yields significant improvements over the standard scheme in terms of attainable fidelity, robustness against noise, and applicability for a variety of non-QND interactions.
UCPH has focused on the design, production and tests of the first generation of microcells. A range of microcells with different size parameters were produced with partly differing production routines and tested afterwards. Due to these investigations, the production of the next generation of microcells which is currently in progress could be optimized to grant better performance, i.e. longer spin lifetimes. This is an important ingredient for the realization of quantum noise limited protocols.
In progress towards a protocol for long-lived entanglement in room temperature atomic ensembles we have theoretically and experimentally analyzed a measurement-assisted dissipative

entanglement generation scheme and showed that use of feedback allows to overcome atomic losses to generate steady-state entanglement.
This work was done in close collaboration between Copenhagen and Munich and has focused on the concrete practical questions arising from the experimental implementation of basic building blocks for quantum networks. The inclusion of time-modulation and feedback in the theoretical toolbox will be important for the next phase of this work package, especially the development of protocols beyond the Gaussian setting.
In another line of work first attempts to realize the teleportation protocol experimentally with macroscopic atomic ensembles, based on the above mentioned teleportation proposals, have been realized. We hope to finish the experiments on teleportation in the course of this year.
LUH has developed a comprehensive theory for quantum noise in the light matter interface based on the Faraday interaction. The theory takes full account of the full level structure of the atomic media suitable for light matter interfaces. It provides a sound and detailed understanding of the decoherence effects due to spontaneously emitted photons. This work has close connection to WP4.
In a next step LUH started a theoretical study of optically thick samples in microcells as developed and studied experimentally by partner UCPH. Currently LUH is investigating the effects of atomic motion in this new regime. This question is important from two perspectives, firstly for improving our understanding of decoherence and noise, and secondly for increasing the capacity of atomic memories.

WP3: Quantum gases

LENS has worked towards the implementation of coherent transfer of information between light and atoms and towards the development of methods for the analysis of the information stored atomic states. In particular we have implemented a versatile set-up where bi-chromatic radiation in a Raman configuration can be shined onto a Bose-Einstein condensate produced in an AtomChip. The AtomChip is also equipped with RF sources for coherent transfer of atoms between internal states in order to realize an atom interferometer capable of fully characterizing the atomic state.
With this set-up we have realized a multi-path atom interferometer which represents the first step towards the realization of the homodyne detector foreseen as D3.3 in month 36. This interferometer was used to read out the relative phase between two laser beams that had been coherently mapped onto the atoms. In turn this achievement is a considerable step forward towards the realization of a quantum memory with cold atoms foreseen as D3.2 in month 24.
Indeed coherent transfer of information between light and cold atoms is not particularly new however our set-up could offer the possibility of longer storage of information thanks to the reduced perturbations that ultra-cold atoms experience. However the main novelty comes from the availability, unique to degenerate samples, of new techniques of information retrieval based on atomic coherence. Besides their possible advantages in Quantum Information treatment these techniques developed in connection with our theoretical partners in UULM and MPQ could offer novel insights in the Quantum dynamics of the atom-light interface. Indeed in WP4 UULM has developed a chopped random basis (CRAB) optimization algorithm and studied of its feasibility for a closed-loop application to experiments.
MPG has proposed a method to directly measure multi-time correlation functions with a scheme that combines existing spectroscopy techniques with quantum memory technology. The scheme can be applied to the investigation of ultra-cold atoms in optical lattices using the room-temperature atomic-ensemble based quantum memories studied in the MALICIA project.

WP4: Quantum Interfaces

LUH has studied effects of quantum noise in the light-matter interfaces based on Faraday interaction. A theoretical description based on a realistic atomic level scheme and derived from a microscopic foundation for the effective equations of motion of the collective atomic modes and relevant modes of light has been provided. The optimization for a quantum memory protocol for the storage and release of quantum states of light was analyzed in detail.

AU group has developed a theory for the creation and detection of many-body correlations in ensembles of two-level systems interacting with a quantized field and their use for precision metrology. Qudit representations and gates for quantum information processing for the effective Jaynes-Cummings models were proposed and composite pulse sequences allowing for implementation of any unitary operator on the lowest N levels of a harmonic oscillator coupled to a two-level system were developed.
UULM group has developed a chopped random basis (CRAB) optimization algorithm [3,4] to be used for control of many body quantum systems. Performance of the CRAB algorithm has been analyzed in detail and it has been shown that in contrast to standard optimal control methods it effectively leads to the optimal driving fields, also in the cases where no geometrical or physical arguments impose 'natural' choice of function basis.
UCPH group has performed an experiment where the steady state entanglement between two Cesium ensembles at room temperature was prepared despite effects of dissipation and decoherence. It has been achieved via a combination of dissipational state preparation and measurement [5,6] and was only possible due to a careful analysis and control of noise sources.

In conclusion 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. We are confident that our project will have a major impact on current practice in this kind of research, since we are bringing together scientists from working on different platforms. These groups are starting to fertilise 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. The extremely close cooperation between theoretical and experimental scientists, which is hardly seen in projects of similar size is also a mandatory prerequisite for significant progress. In these two aspects, our project could become a case study for a major collaborative effort. It is apparent that the full integration of single photons sources, quantum memories, quantum gates in a fully compatible system, is high-risk research, since for such complex systems not all difficulties which may arise can be foreseen. But we are confident of being able to achieve a high impact and hopefully new avenues for future high-risk/high-impact projects will be opened.