MALICIA
Grant Agreement Number 265522

D4.2 **Theoretical model for Rydberg-blockade induced optical nonlinearities for two-photon gates**

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D4.2 Theoretical model for Rydberg-blockade induced optical nonlinearities for two-photon gates

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. The work of UULM focused on numerical simulation and optimization of the light-matter interface including the Rydberg mediated long range interactions. By means of the time-dependent Density Matrix Renormalization Group in its Matrix Product State (MPS) formulation, and optimization through the Chopped Random Basis (CRAB) method, optimal pulse shapes were found which allow to significantly increase the effective Rydberg blockade radius. AU modelled the propagation of light in a Rydberg-nonlinear medium analytically and numerically. The optical transmission properties are calculated via a classical many-body approach. The single-atom Bloch equations are thereby extended by treating the detuning from the Rydberg level as being locally dependent on the Rydberg population of other levels. It turned out that it is necessary to explicitly account also for fluctuations in the level shift, which adds a new dephasing rate for coherences to the Bloch equations. This improved model shows good agreement with experiments.

The combination of Rydberg blockade induced nonlinearities and photon detection for applications in quantum repeaters was studied by LUH and MPG. In line with previous theoretical and experimental research within MALICIA on the dissipative generation of entanglement this work focused on a recently proposed quantum repeater architectures based on a time-continuous, dissipative dynamics. We proved that at the fundamental repeater level discrete entanglement (in ideal case: Bell states) can be generated deterministically by homodyne detection realizing a continuous Bell measurement and feedback. This can be achieved e.g. with optically thick atomic ensembles where the Rydberg blockade prevents the generation of more than one collective excitation. This protocol tolerates significant levels of transmission losses up to almost 40%. The resulting weakly entangled states can be purified by a dissipative dynamics at the next repeater level. MPG analysed the nesting of these protocols, and showed that the resulting convergence time scales only logarithmically with the distance. In the more traditional framework of quantum repeaters (based on iterated steps of photon transmissions, distillation of stored entangled excitations by means of quantum gates, and entanglement swapping) the use of Rydberg nonlinearities for deterministic quantum gates has been studied previously by LUH (at that time Univ. Innsbruck). Taking imperfections in gate operations into account on a perturbative level, it was shown that deterministic gates can significantly improve the rate of entanglement generation.