PhD Thesis Defense Pau Farrera 'A versatile source of light-matter quantum states based on laser-cooled atoms'

PAU FARRERA

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Wednesday July 25, 15:00 h. ICFO Auditorium

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Quantum Photonics With Solids And Atoms

ICFO-The Institute of Photonic Sciences

Quantum information is a fascinating field that studies situations in which information is encoded as quantum states. This encoding is affected by quantum physical effects (such as superposition or entanglement) and its study has led to exciting discoveries from both fundamental and applied perspectives. An interesting system within this field is a quantum light-matter interface, able to interface quantum states encoded in light and those encoded in matter. These systems can combine the long distance transmission advantage of photonic states with the storage and processing capabilities of matter states.

The main goal of this thesis was to develop a quantum light-matter interface able to distribute the photonic state to other interfaces based on different platforms. This versatility could open new possibilities that combine the advantages of the different platforms. In this thesis we studied the challenges to make these hybrid connections possible and we performed two examples of such connections.

Our quantum light-matter interface is based on a cloud of Rubidium atoms that are laser-cooled in a magneto-optical trap. We operate the atomic system using the Duan-Lukin-Cirac-Zoller scheme in order to generate pairs consisting on a single photon and an atomic collective spin excitation (so-called spin-wave). Spin-waves can later be mapped efficiently into a second single photon, which allows for synchronization capabilities. We use this scheme to generate different types of quantum states, such as heralded on-demand single photons and photonic qubits, photon-photon correlated states, or entanglement between photonic and atomic qubits.

Firstly, we studied two capabilities needed in order to perform the mentioned hybrid connections: the frequency and temporal tunability of the photonic states. In the first one we studied the frequency conversion of the single photons paired with spin-waves in the atomic medium. We could convert their wavelength from 780 nm to 1550 nm using a nonlinear crystal waveguide, while still showing quantum statistics of the field. In the second one we showed a temporal tunability of the single photons with durations ranging from around 10 ns to 10 us. The studied statistics of the fields indicate that the photons are close to Fourier-transform-limited, allowing for photon bandwidth tunability.

In the third work we studied the generation of a light-matter entangled state in which the photonic state is encoded as a time-bin qubit. Two key ingredients enabled this experiment: a magnetic-field-induced atomic dephasing that allows to create spin-waves in two distinguishable temporal qubit modes, and largely imbalanced Mach-Zehnder interferometers that enabled the qubit analysis. Photonic time-bin encoding has the advantages of low decoherence in optical fibers and direct suitability for frequency conversion.

Finally, we took advantage of these studied capabilities in order to transfer photonic quantum states generated by our laser-cooled atomic system to two different types of light-matter interfaces. The first one was a laser-cooled Rubidium cloud able to transfer single photons into Rydberg excitations. We showed that the quantum statistics of our photonic fields are preserved after the Rydberg storage, which represents a first step for future studies of quantum nonlinear effects using the long range Rydberg interaction. The second one was a crystal doped with Praseodymium ions. In this work the photonic quantum state transfer happened between systems with different atomic species, being a truly hybrid example that was enabled by quantum frequency conversion.

These results show a quantum light-matter interface where the properties of the photonic states can be tuned for an optimal interaction with other matter platforms. The proof-of-principle photonic quantum state transfers to the Rydberg and doped-crystal systems open the way to study new experiments that combine advantages of different platforms.

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