Since last century, quantum mechanics and information science had produced a cross-subject: quantum information science. In this field, quantum communications can realize absolute security information exchange; it is becoming the next generation of focus in various national security communication systems and has very likely incalculable impacts on human society economic development. In classical communication, information can be transmitted in long distance by using a repeater of direct amplification. In quantum communications, based on quantum entanglement swapping and quantum storage for realizing quantum repeaters, the information could be transmitted in long distance. Thus, quantum memory as a key quantum logic device to realize the storage and release of information, which is one of the key techniques of quantum computation and quantum networks, affects the practical feasibility of quantum communication. In enhancement of storage capacity, quantum memory based on OAM space can significantly improve the capacity of quantum networks and is very promising to high-capacity quantum networks. For high-speed property, Raman quantum memory has the advantages of broadband, which is the key of high-speed quantum networks. This thesis is mainly on the goal of achieving high-capacity, high-speed quantum memory and focuses on experimental research of storing orbital angular momentum, Raman quantum memory, etc. The works in this paper are very promising in high-speed and high-capacity quantum networks in future.

The main content of this thesis includes:

1. Quantum storage of single photon’s image. We prepare two cold atomic ensembles via magnetic optical trapping technology, which act as our experimental medium. We prepare the heralded single-photon source through spontaneous Raman scattering in one atomic ensemble and encode the single photon with a spatial structure via a spiral phase plate. Via electromagnetically induced transparency storage scheme, we realize quantum storage of single photon carrying orbital angular momentum and its superposition state. At last, the experimental results show that the property of recovery single photon is
remained, and obtain that its spatial coherence is maintained in the storage process.

2. Quantum memory of a high-dimensional state of single photon. Based on the realization of quantum storing single photon carrying orbital angular momentum and encoding the input and projecting output state with spatial modulators and a single-mode fiber, we implement the encode, storage, and measurement of high-dimensional state of true single photon in the storage process. In order to perform the storage of qutrit state, we use nine spatial modes to construct the quantum tomography. The results show that our storage is better for qutrit state. Most importantly, we perform the quantum memory of two special qutrit states of true single photon, which gives the quantum state is retained in our memory well.

3. Quantum storage of two-dimensional OAM entanglement. We prepare two-dimensional orbital angular momentum entanglement between a single photon and atomic spin excitation state through spontaneous Raman scattering in one of the two cold atomic ensembles. Via Raman memory scheme, we input this photon into another atomic cloud for storage, and then, we establish the orbital angular momentum entanglement between these two atomic ensembles. In order to check the nature of quantum entanglement, we transfer the atomic spin collective excitation-entangled state into photonic state. Through performing quantum tomography, calculating the fidelity of storage, checking the inequality of CHSH, and verifying the interference of two photons, we obtain that the entanglement of orbital angular momentum is highly retained in the storage process.

4. Experimental realization of high-dimensional entanglement storage. Through spontaneous Raman scattering in one atomic ensemble, we prepare orbital angular momentum high-dimensional entanglement between a photon and an atomic spin collective excitation state. Through Raman storage of the photon, high-dimensional entanglement could be established between these two atomic ensembles. In our experiment, we verify the dimension number of entanglement before and after storage by using an entanglement witness. Via the measurement of 11-dimensional orbital angular momentum (quanta $-5 \rightarrow 5$) modes, the results show that 8-dimensional entanglement is stored in our memory, and there is a 7-dimensional entanglement retrieved.

5. Raman quantum memory of photonic polarized entanglement. We realize two storage processes: (1) Raman quantum memory of single-photon hybrid-entangled state between path and polarization and (2) Raman quantum memory of polarization entanglement. In the first process, we prepare the heralded single photon via spontaneous Raman scattering, encode the single photon into hybrid entanglement with a Sagnac interferometer, and realize storage and retrieval processes. In the second process, via an active locking interferometer, we prepare the photonic polarization and atomic ensemble entanglement and store it with the Sagnac interferometer. At last, through quantum tomography, we calculate the fidelity before and after storage to characterize the properties of entanglement.
The main innovations of thesis are:

1. We for the first time realize quantum memory of orbital angular momentum carried by single photon and its superposition state in the world. The results show that the single photon encoded by a spiral phase plate can be stored in our system and retrieved again, and its spatial coherence is maintained in this process. Our experiment creates a new project in quantum memory and brings a new challenge in quantum information field.

2. We realize quantum memory of high-dimensional state of single photon; in our system, the dimension is three. By using our quantum memory device, the qutrit state of single photon can be stored and retrieved with high fidelity. At same time, we explore the situation of the higher dimensional state of single photon and obtain that the different efficiency for different number of orbital angular momentum must be considered in storing higher dimensional state.

3. We achieve the orbital angular momentum entanglement storage based on two atomic ensembles. Through spontaneous Raman scattering process, we first establish the orbital angular momentum-entangled state and establish the entanglement between two atomic ensembles by performing Raman storage. The results give that the primary quantum network node based on orbital angular momentum two-dimensional subspace is established for the first time, which is very promising for realizing high-dimensional quantum network in future.

4. We firstly realize high-dimensional entanglement storage based on two atomic ensembles. We prepare the high-dimensional entanglement in orbital angular momentum space through spontaneous Raman scattering process and establish the high-dimensional entanglement between two atomic ensembles via Raman storage scheme for the first time. We successfully realize a quantum memory of eight-dimensional entangled state, and the retrieved number of entanglement dimension is seven. We firstly give the feasibility of high-dimensional quantum networks.

5. We realize Raman quantum memory of polarization entanglement in cold atoms for the first time. We realize storing single photon’s hybrid entanglement of polarization and path, and also demonstrate quantum memory of two-photonic polarization entanglement. The quantum storage of photonic polarization entanglement is very promising in realization of high-speed quantum networks based on fiber.

Hefei, China
August 2017

Dr. Dong-Sheng Ding
Broad Bandwidth and High Dimensional Quantum Memory Based on Atomic Ensembles
Ding, D.-S.
2018, XXII, 122 p. 49 illus., 42 illus. in color., Hardcover