Abstract

Quantum networks are composed of quantum nodes which coherently interact by way of quantum channels. They offer powerful capabilities for quantum computation, communication, and metrology. A generic requirement for these realizations is the capability to generate and store quantum states among multiple quantum nodes, and to disseminate these resources throughout the network via the quantum channels (chapter 1). In this thesis, I describe a series of experiments whereby single excitations in atomic ensembles are strongly coupled to optical modes and provide efficient means for the coherent control of entangled states between matter and light (chapter 2).

By following the seminal proposal by Duan *et al.*, we have generated measurement-induced entanglement of an excitation between two cold atomic ensembles. Using this system, we investigated the relationship for the global bipartite entanglement and local correlations in its subsystems (chapter 3).

In addition, we achieved functional quantum nodes for entanglement distribution (chapter 4). Two pairs of remote ensembles at two quantum nodes were prepared into entangled states in a heralded and asynchronous fashion by the conditional controls of the entanglement. The quantum states of the ensembles were then distributed into polarization entangled states of photons. We also prepared an analogous quantum state and transferred the nonlocal coherence between two pairs of heralded entangled atomic ensembles, providing a step towards entanglement connection (chapter 5).

Beyond such probabilistic approaches, we demonstrated an experiment where entanglement between two quantum memories is created by the reversible and deterministic mapping of an entangled state of light via dynamic electromagnetically induced transparency (chapter 6). This experiment opens novel prospects of integrating hybrid quantum systems by way of reversible quantum interfaces between light and matter (chapter 10).

Then, we extended our work to multipartite quantum systems (chapters 7–9). We theoretically investigated the characterization of multipartite mode-entangled states by way of quantum uncertainty relations, and introduced theoretical tools to verify the entanglement orders in multipartite systems (chapter 7). In particular, we achieved entanglement for one delocalized photon among multiple optical modes ($N > 2$) (chapter 8).

Finally, we have achieved measurement-induced entanglement of spin waves among four quantum memories (chapter 9). The individual atomic components for the entangled W state of the four ensembles were

then coherently converted into four propagating entangled beams of light via superradiant emissions. We observed the statistical and dynamic transitions for the multipartite entangled spin waves. Experiments described in this thesis thereby represent significant advances of experimental and theoretical capabilities to generate, store, transfer, and characterize entanglement of matter and light over quantum networks (chapter 10).