Chapter 10

Conclusion and outlook

10.1 Conclusion

So here I am at the very last chapter of my doctoral thesis. I find it difficult not to feel nostalgic about my experience in the Caltech quantum optics group over the past 5 years. I am fortunate to have led and undertaken a 'collective' endeavor of an 'ensemble' of many brilliant scientists. Looking back, my stay at Caltech was a tremendous journey of excitement, passion, trust, and fulfillment shared collectively among my peers and myself, as we faced and solved challenges in the lab. Indeed, this thesis is a result of many people's hard work and collaboration, and I acknowledge their tireless contributions to the body of work for my doctoral thesis, as further summarized in the acknowledgement section. Personally, developing keen fellowship with these people has been by far one of the most meaningful achievements I have made during my time here. I hope that by writing this thesis I have adequately summarized the scientific advances of our experiments in the unifying theme of quantum networks, which we have contributed to a field that has been growing at an explosive pace (chapters 1–2).

In this thesis, I presented a series of experimental and theoretical studies (chapters 3–9), which, I believe, have made important contributions to the field (chapter 1). Following the Duan-Lukin-Cirac-Zoller protocol[4], we have studied in detail the decoherence mechanism for the entanglement stored in two atomic ensembles (ref.[34], chapter 3), demonstrated the first functional quantum nodes for the *DLCZ* quantum network (ref.[36], chapter 4), and made the initial step towards entanglement connection (ref.[37], chapter 5). We have demonstrated the first reversible mapping of photonic entanglement into and out of quantum memories (ref.[30], chapter 6). We have theoretically developed a nonlocal, nonlinear entanglement witness based on quantum uncertainty relations to efficiently characterize multipartite entanglement (ref.[38], chapter 7), and applied the entanglement verification protocol to verify multipartite mode-entanglement for one photon (ref.[35], chapter 8). Finally, we have achieved measurement-induced entanglement of spin waves among multiple quantum memories and opened new prospects towards multipartite quantum networks (ref.[33], chapter 9).

10.2 Outlook

In less than a decade since the initial demonstrations of a quantum interface between light and matter[90,91], light-matter quantum interface has become one of the pillars in the field of quantum information processing and communication, and one of the most active areas of research at the present time. A number of the experiments has made fundamental discoveries of new physical processes of controlling quantum coherence and entanglement, with promising results revealing various paths towards the realization of scalable quantum networks, including those in chapters 3–9.

Despite the remarkable advances, the current state of the art is still primitive relative to that required for the robust and scalable implementation of sophisticated network protocols (see chapter 9). One of the long-standing issues in achieving a large-scale quantum network is the unfavorable laboratory scalability for free-space ensemble-based approaches. Indeed, an important drawback of the current experiments in my thesis is the tremendous technical complexities required to implement even the rudimentary quantum information operations with sufficient fidelities for quantum error-corrections, as vividly illustrated in Fig. 10.1. I believe that this brings a very pragmatic opportunity for us to transit from the present free-space quantum optical laboratory to nano-integrated systems comprised of ultracold atomic ensembles and solid-state spin ensembles interacting on a photonic waveguide circuit.

An initial step towards such a hybrid quantum system was made in 2008 with our proof-in-principle experiment, whereby an entangled state between two cold atomic ensembles was created by the reversible and deterministic mapping of an entangled state of light (ref.[30], chapter 6). More recently, we achieved the coherent transfer of the quantum information stored in multipartite entangled spin waves of four quantum nodes of a network to multipartite entangled beams of light, each propagating through individual photonic quantum channels (ref.[33], chapter 9). Importantly, these recent experiments are natural precursors for creating a 'hybrid' entangled state for many solid-state and spin-wave qubits via the coherent mapping of a photonic entangled quantum bus over a 'lithographically patterned' quantum network.

In addition, I am particularly interested in studying the behavior of quantum entanglement in quantum many-body systems[39,40]. For example, in chapter 9, we investigated the thermal entanglement for the 'spin waves' in quantum magnets and related such thermal spin relaxation processes to the statistical behavior of our system of four atomic ensembles[33]. Creating such theoretical and experimental tools to probe quantum critical phenomena would contribute to the study of quantum entanglement in condensed matter systems and the creation of nonlocal quantum phases that have not heretofore existed[33]. Theoretical investigations of entanglement verification are crucial in this area of research[33,57,121,208], in conjunction with developing experimental tools for quantum information processing (refs.[30,33], chapter 6 and 9).

In line with a broader scope of the program towards a hybrid quantum network, such a lithographic optical network may provide an attractive platform to create and control exotic quantum phases associated with novel 'classes' of entanglement. I am intrigued by the aspect that these quantum phases may be 'induced'

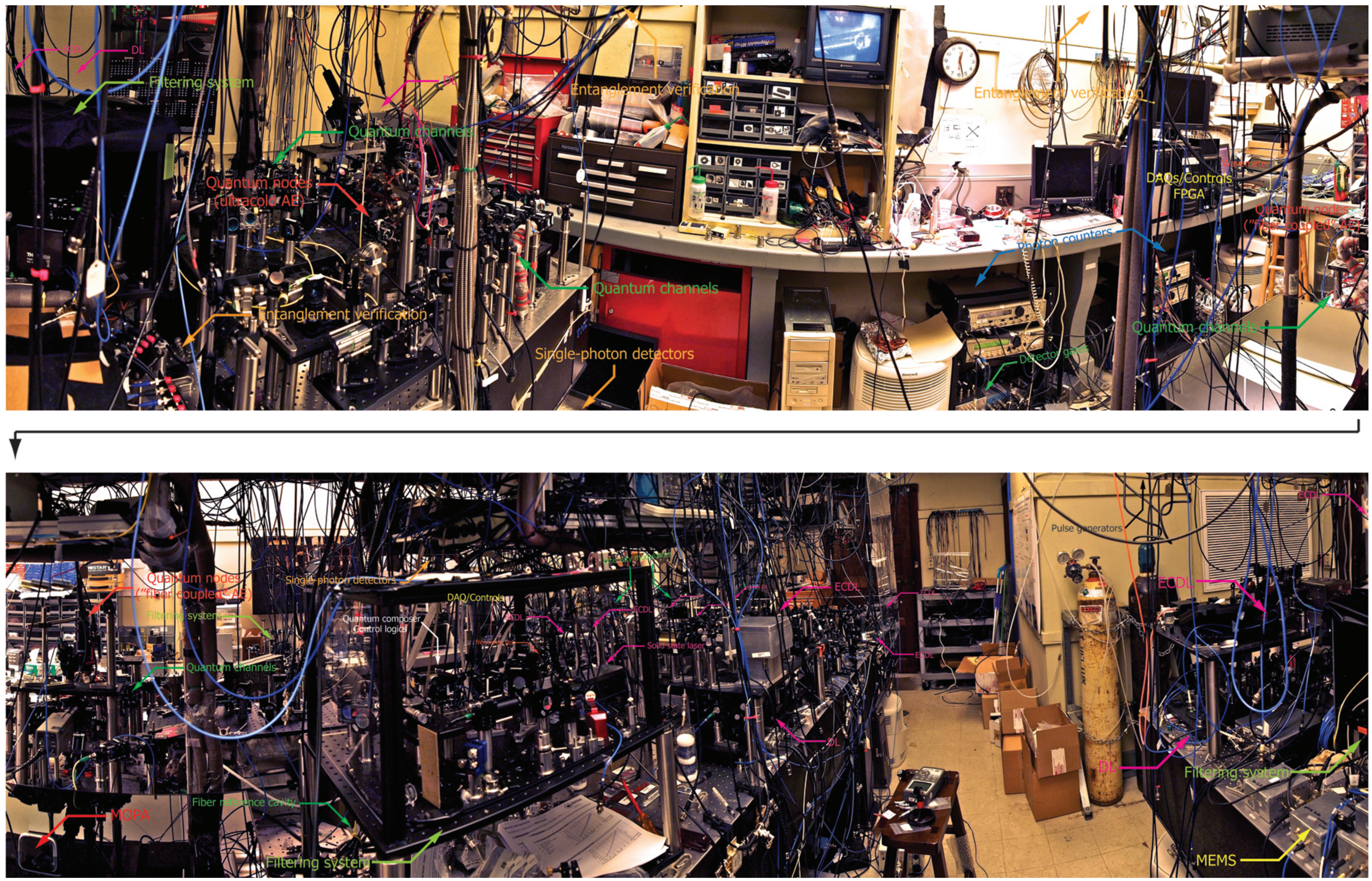

Figure 10.1: **Scaling behavior of laboratory complexity.** A panorama photo of our lab in early 2011. Dazzling complexity is required for laser cooling and trapping, as well as for state-initialization and for generating the classical beams for writing and reading spin waves. A significant portion of the setup is dedicated for laser stabilizations (with a total of 18 lasers operating at the moment), filtering the quantum fields at the single-photon level with high efficiency, and data acquisition. AE: Atomic ensembles, DAQ: Data acquisition system, DL: Diode laser, ECDL: External cavity diode laser, FPGA: Field-programmable gate array, MEMS: Micro-electro-mechanical systems, and MOPA: Master oscillator power amplifier (tapered amplifier).

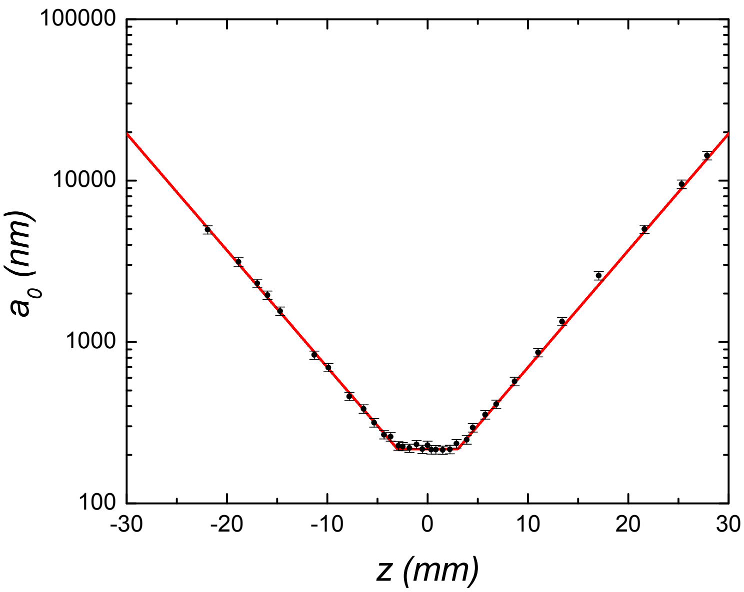

Figure 10.2: **Tapered fiber profile measured by a scanning electron microscope (SEM).** We show the tapered fiber profile based on SEM images taken by Daniel Alton and Clement Lacroute for a pulled SiO_2 fiber. The theoretical line (red line) is based on a simple model of volumetric conservation of the initial cylindrical fiber for a given hot-spot region, which results in an exponential tapering of the fiber radius[301]. The fiber radius at the center is $a_0 \simeq 250$ nm over a flat region of $z_0 \sim 6$ mm.

with nonlocal interactions of atomic pseudo spins and electronic spins by quantum-state exchanges and teleportation over quantum networks[8]. The research performed towards this end is both of fundamental interest for enhancing our understanding of quantum physics and of potential technological importance. Its highly interdisciplinary character encompasses a broad spectrum of fields in physics as well as in computer science and information theory.

10.3 Trapping atomic ensembles with evanescent waves of a nanofiber

Along this line, my colleagues and I are now involved in a long-term program of integrating 'quantum transistors' of atom-like qubits and 'quantum interfaces' to achieve connectivity for the quantum information stored in spin-wave quantum memories[1] to single photons and phonons, with the 'quantum wiring' provided by the quantum circuits imprinted on nanophotonic structures[139,302]. Recent advance includes the observations of electromagnetically induced transparency for trapped ultracold atoms in hollow core fibers[303–306], as well as the trapping and probing of atomic ensembles via the evanescent fields surrounding tapered nanofibers[291,307–309].

While prominent examples of off-resonant interaction between evanescent waves and matter have used planar dielectric geometry for atom optics and interferometry[310–312] as well as for surface traps of quantum degenerate gases[313–315], recent progresses of atom-light interactions with optical waveguides[291,305–309] set the stages for the fiber integrations of free-space quantum systems in a quantum network (chapters 3–9)

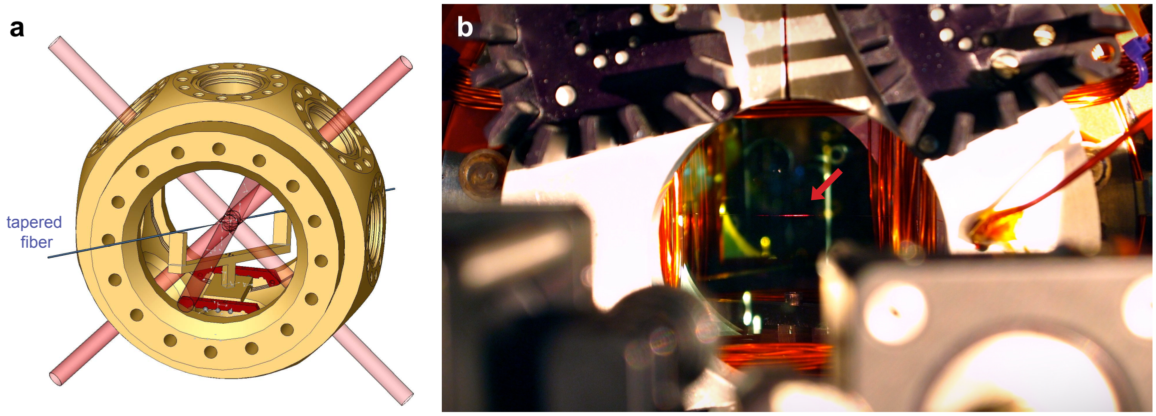

Figure 10.3: **A nanofiber trap for atomic ensembles. a**, CAD drawing (Solidworks) of the fiber trap setup. **b**, A photo of the nanofiber probing laser-cooled cesium atoms in a UHV chamber. The red glow of the tapered nanofiber is due to the Rayleigh scattering of blue-detuned evanescent fields ($\lambda_b = 687$ nm).

via quantum-state transfer between matter and light[30,33] and for the localization and strong coupling of single atoms and photons near microcavities[153,316]. Furthermore, these effective 1-dimensional systems may be applied for investigating quantum many-body phenomena with long-range interactions mediated by the waveguide[317].

As a first step, my colleagues and I have been investigating a nanofiber atom trap ($a_0 = 200 \sim 250$ nm radius), for which single atoms can be trapped within the small mode-volume of the evanescent fields. Inspired by the initial experiments[133,291,292,318], we have theoretically developed a novel state-insensitive two-color fiber trap to increase coherent times τ_c and trap life time τ_t (Fig. 10.5). As illustrated in Fig. 10.5, the engineered potential U_{trap} provides 3-dimensional confinement for trapping single atoms 150 nm away from the nanofiber with trap depths up to $U_{\text{trap}} \simeq 0.5$ mK (ref.[319]).

Recently, we have fabricated such a nano-thin tapered optical fiber from a flame-brushing technique with hydrogen torch in lab 1 (for a nice review of diverse techniques used for tapered fiber fabrication, I refer to ref.[320]). While Daniel Alton, Clement Lacroute, and Tobias Thielle in lab 1 led the responsibility for the fiber fabrication and the pulling setup[321], Aki and I have also contributed to the characterization of the polarization properties of the fabricated nanofibers and to the theoretical understanding of the fiber pulling process[301,320,322–325]. In particular, Daniel Alton and Clement Lacroute can now pull fibers quite consistent with the theoretically simulated fiber profile[301], as shown by Fig. 10.2.

We have placed such a nanofiber in our vacuum chamber shown in Fig. 10.3 and we are currently working towards trapping an atomic ensemble around the fiber. We have observed the transmission spectrum T with thermal cesium atoms released from a magneto-optical trap by the near field of the optical nanofiber in Fig. 10.4a and determined a resonant optical depth of $d_0 = (5.8 \pm 0.3) \times 10^{-3}$ by a probe laser E_p at the $6S_{1/2}, F = 4 \leftrightarrow 6P_{3/2}, F = 5$ transition. From the measured phase space density, we extrapolate that only ~ 1 atom is present on average within the interaction volume. We also measured the saturation effect of the atomic dipole via the evanescent field E_p, and studied preliminary results for the mechanical effects of

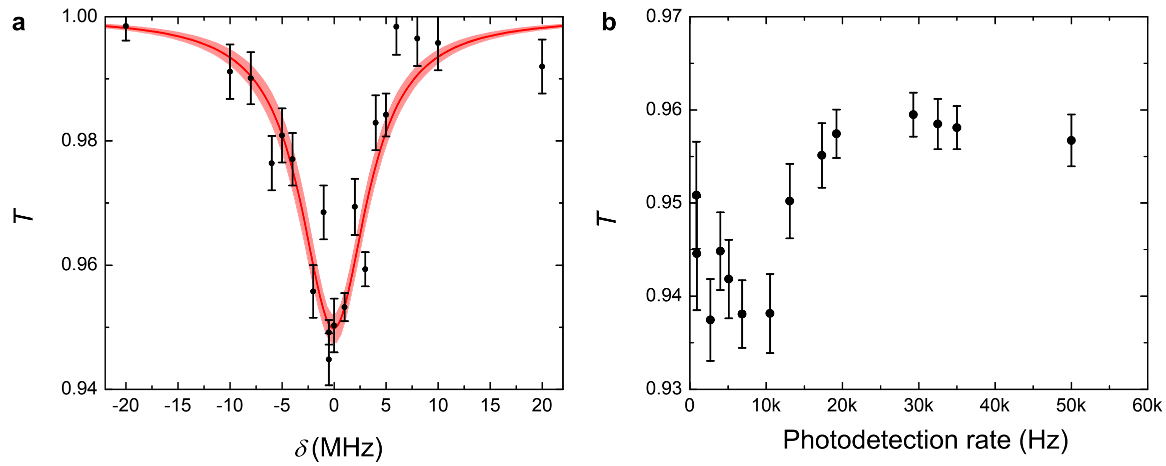

Figure 10.4: **Probing cold atoms with a tapered nanofiber. a**, The evanescent field of the tapered nanofiber is used to probe the transmission T of the nanofiber near the cycling transition $F = 4$ $(6S_{1/2}) \leftrightarrow F = 5$ $(6P_{3/2})$ of atomic cesium, as a function of detuning δ. The measured linewidth of the transition is $\Gamma = 7.7 \pm 0.9$ MHz, with a small optical depth $d_0 = (5.8 \pm 0.3) \times 10^{-2}$ on resonance, due to the limited phase space density of the magneto-optical trap at the time. The red band is the $1/e$ confidence level of a Lorentzian fit. **b**, Observation of saturation effects for thermal atoms nearby a nanofiber.

the atoms by the probe laser. Theoretically, we are further exploring novel state-insensitive trapping geometries with the adiabatic trapping potential predicted in Fig. 10.5. The details of the theoretical calculations, however, will be discussed elsewhere.

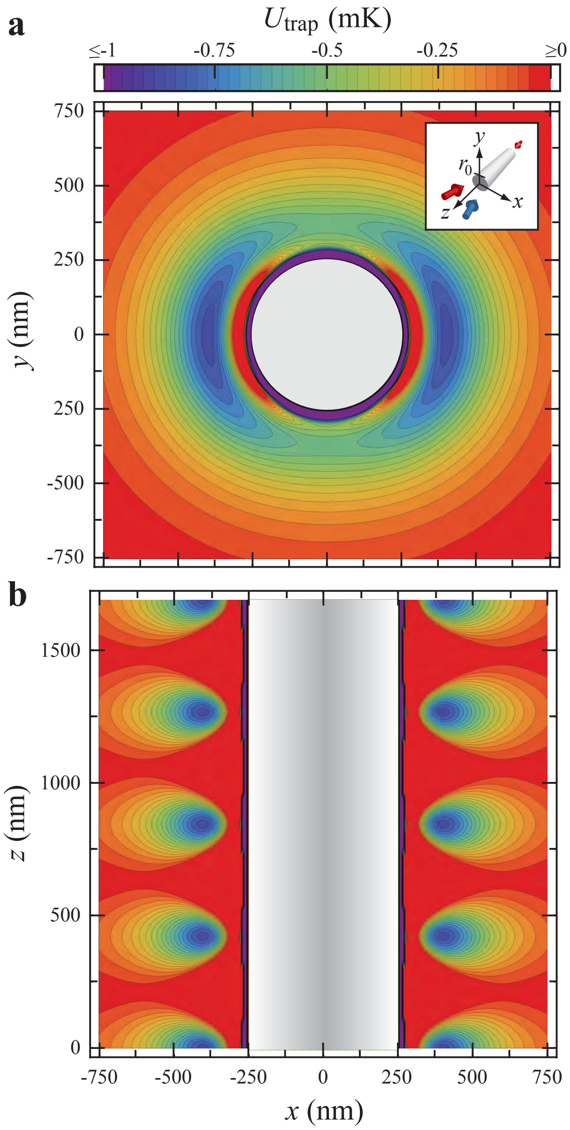

Figure 10.5: **Trapping single atoms with nanofibers.** A two-color optical trap around a nanofiber[319]. The trapping potential U_{trap} is generated by two evanescent fields that provide a 3D confinement for the trapped atoms outside the 500 nm diameter optical fiber, shown in **a**, the x-y plane, and in **b**, x-z plane. Specifically, U_{trap} results from two counter-propagating red-detuned beams (935 nm, red arrows), and a blue-detuned beam (687 nm, blue arrow) in a 'magic' configuration, as shown in the inset. The standing wave structure of the attractive red-detuned field and the repulsive force from the blue-detuned beam enable trapping of single atoms at each node of U_{trap} near the dielectric waveguide despite the strong surface potential U_{surface}, thereby reducing collisional and motional dephasing of spin waves.