Interacting single atoms with nanophotonics for chip-integrated quantum networks

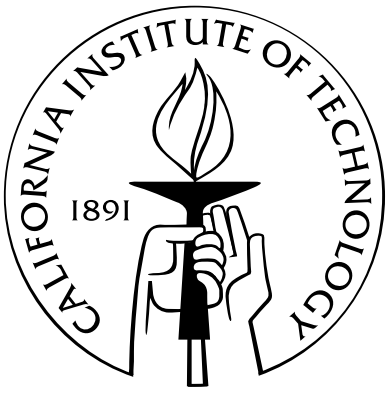
Thesis by

Daniel James Alton

In Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy



California Institute of Technology

Pasadena, California

2013

(Defended May 22, 2013)

To my parents, sister, and loved ones.

Acknowledgments

First and foremost, I would like to thank God, the Almighty, for all of His blessings.

I would like to thank my advisor, professor Jeff Kimble, a mentor who I greatly respect and admire. Not just as a great scientist with exceptionally high standards of rigor and integrity, but it never cease to amaze me, professor Kimble's depth and breadth of thinking. Looking into matters from the biggest horizon to the smallest details, connecting the many dots and people to the matter, and looking far into the future and down to the shortest time scales in the experiment. It has been a great privilege and I am deeply grateful.

I would like to thank our collaborators, professor Kerry Vahala and professor Oskar Painter, for sharing their pioneering expertise and leadership in the development of novel photonic devices, with very high, world-record quality, which have been critical in the work described in this thesis. My thesis committee members, professor Jeff Kimble, professor Kerry Vahala, professor Olexei Motrunich, and professor Michael Roukes, who have been extraordinary sources of inspirations, thank you very much.

My sincere gratitude to professor Peter Zoller and professor Jun Ye, visiting professors in our group who have shared their insights and advice for certain parts of the work described in this thesis. To professor Jun Ye, for inviting me to spend a week at his laboratory at JILA, Boulder, Colorado, to learn about the making of optical amplifiers, and to the members in the Ye group, especially Sebastian Blatt.

The work described in this thesis is a result of contributions and hard work of many individuals that I would like to acknowledge here. In the experiments with microtoroidal resonators: Takao Aoki, a very talented scientist and experimentalist that I admire and learn greatly from; Scott Parkins, who enlightened us with the fundamental theoretical formulations especially in our photon router work; Nate Stern, a multi-talented scientist whose work and drive I admire both in the experimental and theoretical parts of our work; Hansuek Lee and Eric Ostby from Vahala group, highly talented individuals who shared their expertise and fabricated the wonderful microtoroidal photonic devices

critical in our experiments; last but not least, Cindy Regal and Barak Dayan, extraordinary scientists whose works are simply amazing. In the experiments with optical nanofibers: Kyung Soo Choi and Akihisa Goban, extraordinarily talented and accomplished young scientists who I especially commend and thankful to not just for our collaboration in the lab but also outside of the lab for our enduring friendship. Ding Ding, Clement Lacroute, Martin Pototschnig, and Tobias Thiele, who made important contributions in our nanofiber trap work. In the experiments with photonic crystal based structures: Firstly in Lab 11, Akhisa Goban and Chen-Lung Hung whose cold atom transport design formed the basis of the experimental setup in Lab 1 discussed in this thesis. Chen-Lung's extraordinary talent and exceptionally open-minded approach had been critical and greatly valuable in the projects; The photonic crystal based device design/characterization/fabrication team: Su-Peng Yu, Jonathan Hood (Kimble group), Richard Norte, Sean Meneehan, and Justin Cohen (Painter group), whose work have been critical in our experiments; In Lab 2: Jae Hoon Lee, Juan Muniz, and Ding Ding; Thanks especially to Juan Muniz for our close collaboration in investigating atom trapping schemes, where Juan's great talents and contributions have been critical; Last but not least, the team in Lab 1 who have directly worked in the photonic crystal based experiments discussed in this thesis: Andrew McClung, an exceptionally talented researcher and computer expert whose combination with out-of-the-box thinking have led to various major contributions in our lab; Pol Forn-Diaz, a very talented scientist with broad interests and at the same time extraordinary attention to details, who I greatly respect and am thankful for to have worked together inside and outside of the lab; Martin Pototschnig, an insightful and highly talented experimentalist, who is capable of achieving amazing results especially when the insights are unleashed; and Clement Lacroute, for his important and valuable contributions. I also want to acknowledge Taofiq Paraiso and Alex Krause from Painter group.

I would like to thank the members of the Kimble group (Caltech Quantum Optics group), Vahala and Painter groups, and the Institute for Quantum Information and Matter (IQIM) at Caltech, who have been great sources of inspirations, friendships and supports at various locations, times, and situations, I am greatly thankful for these years where our paths have crossed, and hopeful that they will again in the future. In addition to the above-mentioned, I would like to specifically thank: Dalziel Wilson, Yi Zhao, Kang-Kuen Ni, Scott Papp, Russ Miller, Hui Deng, Tracy Northup, Julien Laurat, Elizabeth Wilcut Connolly, Scott Kelber, Daniel Chao, Sarah Kaiser, Michael Martin, Jiang Li, Kiyoul Yang, Darrick Chang, Alexey Gorshkov, Liang Jiang, K C Fong, and Matt Eichenfield. I would like to thank Scott Curtis our group's administrator who always got the job done exceptionally

well regardless of the number of lines, people, organizations, or challenges involved. I also want to thank several particular administrators in the Physics department, Donna Driscoll, Marcia Brown, Alan Rice, Louisa Fung, and Loly Ekmekjian.

I would like to take this opportunity to thank my undergraduate research advisors, Prof. Ping Koy Lam, Prof. Tim Ralph, and Dr. Thomas Symul, at Australian National University and University of Queensland, who have introduced me to the world of quantum optics, to whom I am greatly and always be thankful.

I would like to thank my parents, sister, and grandparents, who have given their endless support, inspirations, and love in my life. I am forever grateful for their sacrifices, guidance and faith in me. Despite the extend of the oceans, masses of land, and the four different time zones that I have lived in for extended periods of time, they have always been there. I am blessed to have met a very special person whom I hold close and dear, who has enriched my life in every aspect since the last two years. I thank her for all the love and support. It is to them, I wish to dedicate this thesis.

Daniel Alton

May 2013

Pasadena, CA

Abstract

Underlying matter and light are their building blocks of tiny atoms and photons. The ability to control and utilize matter-light interactions down to the elementary single atom and photon level at the nano-scale opens up exciting studies at the frontiers of science with applications in medicine, energy, and information technology. Of these, an intriguing front is the development of quantum networks where $N \gg 1$ single-atom nodes are coherently linked by single photons, forming a collective quantum entity potentially capable of performing quantum computations and simulations. Here, a promising approach is to use optical cavities within the setting of cavity quantum electrodynamics (QED). However, since its first realization in 1992 by Kimble et al., current proof-of-principle experiments have involved just one or two conventional cavities. To move beyond to $N \gg 1$ nodes, in this thesis we investigate a platform born from the marriage of cavity QED and nanophotonics, where single atoms at ~ 100 nm near the surfaces of lithographically fabricated dielectric photonic devices can strongly interact with single photons, on a chip. Particularly, we experimentally investigate three main types of devices: microtoroidal optical cavities, optical nanofibers, and nanophotonic crystal based structures. With a microtoroidal cavity, we realized a robust and efficient photon router where single photons are extracted from an incident coherent state of light and redirected to a separate output with high efficiency. We achieved strong single atom-photon coupling with atoms located ~ 100 nm near the surface of a microtoroid, which revealed important aspects in the atom dynamics and QED of these systems including atom-surface interaction effects. We present a method to achieve state-insensitive atom trapping near optical nanofibers, critical in nanophotonic systems where electromagnetic fields are tightly confined. We developed a system that fabricates high quality nanofibers with high controllability, with which we experimentally demonstrate a state-insensitive atom trap. We present initial investigations on nanophotonic crystal based structures as a platform for strong atom-photon interactions. The experimental advances and theoretical investigations carried out in this thesis provide a framework for and open the door to strong single atom-photon interactions using nanophotonics for chip-integrated quantum networks.

Contents

List of Figures

List of Tables