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To my parents,

Hassan and Shahnaz,

Acknowledgements

Tracing back my interest in science always takes me to my pre-school years when my mother would challenge me with her well thought out questions about the how's and why's of nature; questions spanning different realms of science ranging from formation of galaxies to the wild habitats of deserts. Soon after learning how to read, she prompted me to study numerous "science for kids" books and write short summaries about each one. Deeply indulged by the beauty of science, I still find myself walking in the same path she helped me toddle along for the first time. I was also fortunate to have the support of a father, who besides being a physics teacher, had an incredible talent in fine arts. Spending summer times in his art gallery, drawing and painting next to him, prepared me to be observant, attentive to details and intuitive. In a way, my Ph.D. degree in physics is the crop of the seeds they planted years ago by their immaculate training and never-ending sacrifices. To them, I wish to dedicate this thesis.

As a new graduate student to Caltech, I had ample time to discover my research interests among a myriad of exciting opportunities at this extraordinary institution. However, after a brief encounter with Prof. Kerry Vahala, I was confident that I wanted to pursue my Ph.D. studies under his supervision. What I sensed during our first conversation and proved to be absolutely accurate in the years to come, was Prof. Vahala's genuine interest in his students' scientific progress, academic success, and professional excellence. His grand-scheme management style has granted me the freedom and independence without which my achievements would have been of less significance and flavor. Not only his intuition and authentic interest in science has awakened my enthusiasm in the fundamental questions of nature, but also his fatherly advice on different aspects of a business career has been invaluable in planning my future outside academia. I would like to consider my insignificant contribution to his scientific accomplishments, as a sign of gratitude for all I was offered during my Ph.D. studies in his research group.

I have also enjoyed interacting with all my group members, including Sean Spillane, Bumki Min, Lan Yang, Sameer walavalkar, and Andrea Martin. Deniz Armani's humor and lively company has always been a source of energy in the arduous days of laboratory work. I am particularly grateful to involvement of Tobias Kippenberg and Tal Carmon in my recent work on "radiation-pressure-induced instability," and generous contribution of Mani Hossein-Zadeh in my concluding studies on "Brownian noise."

Although my tenure at Caltech is about to end, I truly believe that the life-changing lessons I have learned here, will prove to be of profound impact throughout my entire life.

Pasadena, October 26, 2005

List of Publications

[1] H. Rokhsari, and K. J. Vahala. Ultralow loss, high Q, four port resonant couplers for Quantum Optics and Photonics. *Physical Review Letters*, 92(25): art. no. 253905, 2004.

[2] H. Rokhsari, S. M. Spillane, and K. J. Vahala. Loss characterization in microcavities using the thermal bistability effect. *Applied Physics Letters*, 85(15): 3029-3031, 2004.

[3] H. Rokhsari, and K. J. Vahala. Observation of Kerr nonlinearity in microcavities at room temperature. *Optics Letters*, 30(4): 427-429, 2005.

[4] T. Carmon, T. J. Kippenberg, L. Yang, H. Rokhsari, S. M. Spillane, and K. J. Vahala. Feedback control of ultra-high-Q microcavities: applications to micro-Raman lasers and microparametric oscillators. *Optics Express*, 13(9), 2005.

[5] H. Rokhsari, T. J. Kippenberg, T. Carmon, and K. J. Vahala. Radiation-pressure driven micro-mechanical oscillator. *Optics Express*, 13(14), 2005.

[6] T. J. Kippenberg, H. Rokhsari, T. Carmon, and K. J. Vahala. Analysis of radiation pressure-induced mechanical oscillation of an optical microcavity. *Physical Review Letters*, 95: art. no. 033901, 2004.

[7] T. Carmon, H. Rokhsari, L. Yang, T. J. Kippenberg, and K. J. Vahala. Temporal behavior of radiation-pressure-induced vibrations of optical microcavity phonon mode. *Physical Review Letters*, 94, art. no. 223902, 2005.

[8] H. Rokhsari, M. Hossein-Zadeh, and K. J. Vahala. Observation of Brownian noise in optomechanical oscillators. Manuscript in preparation.

Abstract

Optical microcavities are indispensable from numerous scientific studies and have also found applications in a vast array of technologies. Ultra-high-Q microtoroids, used throughout this thesis, belong to the category of surface-tension-induced-microcavities that have proved to provide the highest quality factors to date. High efficiency coupling of optical power to these cavities has also been realized by extremely low-loss tapered optical fibers. Combination of ultra-high-Q microcavities and tapered fibers can hence result in minimizing optical loss in various studies, which is often the main obstacle in realizing distinct physical functionalities. Using these tools, an almost ideal design is developed for optical power transfer between two distinct waveguides where efficiency is solely limited by intrinsic losses of the optical resonator. These intrinsic loss mechanisms are experimentally studied and differentiated by a powerful technique based on thermal nonlinearities of the microcavity material. Important information about the interaction between cavity surface and the ambient environment has been obtained through this study.

Enormous power buildup in microcavities, due to their negligible optical loss, makes them suitable for studying various nonlinear phenomena with extremely low optical powers typically in the range of a few micro-Watts. Optical Kerr nonlinearity usually masked by dominant thermal effects is studied in this thesis. Taking advantage of slow response times of thermal effects, an innovative pump and probe technique is developed to unveil and measure the Kerr nonlinearity in microcavities, for the first time, at room temperature. The technique also enables accurate measurements of thermal response times in microcavity structures.

Whispering-gallery microresonators have historically been perceived as structures that could efficiently confine optical energies. This is due to their exceedingly low losses at optical frequencies. This thesis has, for the first time, explored these structures in a starkly different frequency range. Optical microcavities like any other structure have mechanical eigenmodes or resonant modes of vibration with quality factors representing the efficiency of energy storage at mechanical frequencies. It is shown here that micron size of these structures results in vibrations at radio frequencies (~1-100 MH), about seven orders of magnitude apart from the optical frequencies (~100 THz). Mechanical quality factors in excess of 5,000 are measured for toroidal microcavities at their eigenfrequencies of vibration, revealing a heretofore unknown potential of these structures in storing energy at frequencies remarkably distant from their optical resonant modes.

This thesis describes how radiation-pressure or the force due to impact of photons could result in exceptionally strong coupling between the mechanical and optical resonators collocated within the same device. The discovered optomechanical coupling present in toroid microcavities is shown to reach such a high level that regenerative mechanical oscillations of the cavity structure are initiated with only micro-Watts of optical power. This is the first demonstration of radiation-pressure-induced mechanical oscillations in any type of optomechanical system. Embodied within a microscale, chip-based device, this mechanism can benefit both research into macroscale quantum mechanical phenomena and improve the understanding of the mechanism within the context of Laser interferometer gravitational-wave observatory (LIGO). It also suggests that new technologies are possible that will leverage the phenomenon within photonics.

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