Nonlinear Optics in Ultra-high-Q Whispering-Gallery Optical Microcavities

Thesis by

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In Partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy

California Institute of Technology
Pasadena, California

2004
(Defended May 14, 2004)

To my parents,

Hans and Karola,

Acknowledgements

First and foremost I would like to thank my academic advisor, professor Kerry Vahala, for the support and guidance he has provided me throughout my dissertation, but also for the freedom he has given me to choose my research topics. He created a space in which ideas could be explored without financial constraints. His scientific intuition and insights have always been very helpful. Despite his at times busy schedule, he has always made time for discussion. In addition to the scientific side, he has also provided me with invaluable help in carefully planning and managing research projects. I have always appreciated his calm, precise and carefully evaluating manner. I have truly learned a lot during my thesis, which go beyond science itself, and thank professor Vahala for this. Also, he had always had patience for the many, sometimes quiet extended, trips to Europe I took during my dissertation.

Caltech is a truly special place, and I have deeply enjoyed having the privilege to do my graduate work at such a unique institution, which hosts so many great minds. I have enjoyed taking classes here, and it was my pleasure in particular to take classes from great teachers, in particular Kerry Vahala, Hideo Mabuchi, Jeff Kimble and Amnon Yariv. In the initial stages of my graduate work, I have greatly profited from the experimental skills that my colleagues Dr. Per Olof Hedekvist, Dr. Oskar Painter, Ashish Bhardwaj and Ming Cai have taught me. During my thesis work, I have enjoyed interacting with other students and post-docs of my group, Dr. Mark Brongersma, Bumki Min, Deniz Armani, Lan Yang and Hossein Rokhsari. In particular I have enjoyed working with Sean Spillane, and we have been a team from the first day I joined the group. I have shared an office and experimental setup with him during my entire thesis, and our healthy competitive nature has always benefited us both. We have equally shared the successes as well as the failures, and working together has always been a source of motivation for me. It was a pleasure to work with Sean, and I thank him for the many interesting and stimulating discussions throughout the years.

In addition I have enjoyed working together with Professor Albert Polman from the AMOLF institute during his sabbatical year in the group of professor Atwater in 2003. It was my pleasure to collaborate with him, and he provided me great insights into a different area -material science-. I truly enjoyed our many stimulating and interesting discussions, and I am glad to have had the opportunity to meet him.

Outside of Caltech, I would like to thank my friends, Will Green and Andy Westhead, for their friendship over the past 5 years. They have helped me many times. I also thank Will Green for teaching and helping me with micro fabrication techniques. In addition I have had great pleasure to join a team of highly motivated and talented group of triathletes. Thanks to them, I always was well equilibrated and explored Southern California. In particular I would like to thank Richard Byrd, John Moss, Matt Connery and Peter Meinhold for taking me along on countless rides to the Seal Beach, Malibu Creek canyon and to Mount Wilson. During the few thousands miles we have cycled together I have enjoyed their friendship. The sometimes quiet intense training not only showed me the limits of my endurance, but it also helped me to achieve my goals outside of athletics.

Special thanks goes also to Carl Hansen, for his patience waiting for me on our early-morning bike-rides (often more than the academic five minutes), which have become a regular habit in the last three years. I will certainly miss the obligatory Peet's coffee and the interesting and stimulating discussions with him!

Last but not least, I wish to thank a special group of people. I am fortunate to have met Anna Fontcuberta-i-Morral who has enriched my life in every aspect in the last two years. I thank her for all the love and support. In addition, I wish to thank my parents, my mother Karola and my father Hans and my brother Colin, for their support, love and patience during my entire time at Caltech. Their support and help, went far beyond the true fortune they have spend on transatlantic flights for me! In particular my father Hans, who I deeply admire, has provided me with invaluable advice and help during my entire thesis, and helped me maneuver many challenging situations. He was a constant source of inspiration and motivation for me. It is to them, I wish to dedicate this thesis.

Pasadena, May 4^{th} 2004

List of Publications

[1] T. J. Kippenberg, S. M. Spillane, and K. J. Vahala. Modal coupling in traveling-wave resonators. *Optics Letters*, 27(19):1669–1671, 2002.

[2] S. M. Spillane, T. J. Kippenberg, O. J. Painter, and K. J. Vahala. Ideality in a fiber-taper-coupled micro-resonator system for application to cavity Quantum Electrodynamics. *Physical Review Letters*, 91(4):art. no.–043902, 2003.

[3] S. M. Spillane, T. J. Kippenberg, and K. J. Vahala. Ultralow-threshold Raman laser using a spherical dielectric microcavity. *Nature*, 415(6872):621–623, 2002.

[4] B. K. Min, T. J. Kippenberg, and K. J. Vahala. Compact, fiber-compatible, cascaded Raman laser. *Optics Letters*, 28(17):1507–1509, 2003.

[5] T. J. Kippenberg, S. M. Spillane, B. Min, and K. J. Vahala. Theoretical and experimental analysis of stimulated and cascaded Raman scattering in ultra-high-Q optical microcavities. *Selected Topics Journal of Quantum Electronics*, submitted(2004).

[6] D. K. Armani, T. J. Kippenberg, S. M. Spillane, and K. J. Vahala. Ultra-high-Q toroid microcavity on a chip. *Nature*, 421(6926), 2003.

[7] T. J. Kippenberg, S. M. Spillane, D. K. Armani, and K. J. Vahala. Fabrication and coupling to planar high-Q silica disk microcavities. *Applied Physics Letters*, 83(4):797–799, 2003.

[8] T. J. Kippenberg, S. M. Spillane, D. K. Armani, and K. J. Vahala. Ultralow threshold microcavity Raman laser on a microelectronic chip. *Optics Letters*, 2004.

[9] T. J. Kippenberg, S. M. Spillane, and K. J. Vahala. Kerr nonlinearity induced optical parametric oscillation in a toroid microcavity. *Physical Review Letters*, submitted(2004).

Abstract

Optical microcavities confine light at resonant frequencies for extended periods of time and fundamentally alter the interaction of light with matter. They are the basis of numerous applied and fundamental studies, such as cavity QED, photonics and sensing. Of all resonant geometries, surface tension-induced microcavities, such as silica micro-spheres, exhibit the highest Q-factor to date of nearly 9 billion. Despite these high Q-factor and the intense interest in these structures, the nonlinear optical properties of silica micro-spheres have remained nearly entirely unexplored. In this thesis the nonlinear optical phenomena which can occur in ultra-high-Q microcavities are investigated. To efficiently excite the whispering-gallery modes, tapered optical fibers are used and the coupling to ultra-high-Q modes studied. It is found, that microcavities with ultra-high enter a regime where scattering of light into the degenerate pair of clockwise and counter-clockwise mode is the dominant scattering process. In this regime the coupling properties are significantly altered, but the cavities still retain their ability to achieve significant cavity build-up fields. This allowed exceeding the threshold for all common nonlinearities encountered in silica. In particular, stimulated Raman scattering is observed in taper fiber coupled silica micro-spheres at threshold levels typically in the micro-Watt range, which usually is considered the regime of linear optics. Cascaded Raman lasing is also observed in these structures. The tapered optical fiber in these experiments functions to both pump WGMs as well as to extract the nonlinear Raman fields. In addition, the tapered-fiber coupling junction is highly ideal, making it possible to strongly over-couple ultra-high-Q cavities with negligible junction loss. This feature allows for the observation of very high internal differential photon conversion efficiencies approaching unity. Whereas micro-spheres are both compact and efficient nonlinear oscillators, their fabrication properties lack the control and parallelism typical of micro-fabrication techniques. A synergistic approach of micro-fabrication and a laser assisted reflow process, allows to create toroidally silica microcavities on a chip. In this thesis it is demonstrated, that these cavities can exhibit ultra-high-Q whispering-gallery modes, allowing to achieve ultra-high-Q modes on a chip. This results is a nearly four-order of magnitude improvement with respect to other wafer-scale microcavities. In addition their azimuthal mode-spectrum is strongly reduced. Nonlinear oscillation in these cavities has also been studied, and stimulated Raman scattering observed, allowing to achieve the first Raman laser on a chip. The devices show improved performance compared to micro-spheres due to a strongly reduced azimuthal mode spectrum, which allowed to observe single mode emission. The enhanced geometric control of these cavities is also studied and found to profoundly alter the nonlinear optical processes the toroid microcavities. Reduction of toroidal cross section is observed to cause a transition from stimulated Raman to parametric oscillation regime. This allowed to observe Kerr nonlinearity induced parametric oscillation in a microcavity for the first time. The parametrically generated "twin beams" exhibit high conversion efficiency and show near unity signal-to-idler ratio.

Contents

[1] This chapter has appeared in "Modal Coupling in traveling-wave resonators" *Optics Letters*, 27 (19) 1669-1671, 2002.

[2] Work presented in this chapter has been published in: "Ultra-low threshold Raman laser using a spherical microcavity", *Nature*, 415, 621-623 (2002).

[3] Work in this chapter has been published in: "Fiber-coupled cascaded Raman laser", Optics Letters, 2003 and "Theoretical and Experimental Analysis of Stimulated Raman scattering in ultra-high-Q optical microcavities", submitted (JSTQE).

[4] Section 1.1-1.3 have appeared in: "Ultra-high-Q toroid microcavity on a chip", *Nature,* 421, No. 6926 (2003). Remaining sections are in preparation (2004).

[5] This chapter has been published in "Fabrication and coupling of high-Q silica disk microcavities", Applied Physics Letters, 83(4), p.797-799 (2003).

[6] Work in this chapter has appeared in "Ultra-low threshold microcavity Raman Laser on a microelectronic Chip", *Optics Letters*, Vol. 29, No. 11 (2004).

[7] This chapter has been submitted to *Physical Review Letters* (2004)

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Glossary of Acronyms

WGM Whispering-gallery mode

XPM Cross-phase modulation

FWM Four-wave mixing

UHQ Ultra-high Q

SPM Self-phase modulation

SEM Scanning electron microscope

SRS Stimulated Raman scattering

SBS Stimulated Brillouin scattering

STIM Surface-tension-induced microcavity

LL Light-in light-out

FSR Free-spectral-range

OSA Optical spectrum analyzer