



# Cavity Optomechanics Cavity Optomechanics

**Anna Naomi Pearson**

## **Cavity Optomechanics**

*Cavity Optomechanics* Markus Aspelmeyer, Tobias J. Kippenberg, Florian Marquardt, 2014-07-05 During the last few years cavity optomechanics has emerged as a new field of research. This highly interdisciplinary field studies the interaction between micro and nano mechanical systems and light. Possible applications range from novel high bandwidth mechanical sensing devices through the generation of squeezed optical or mechanical states to even tests of quantum theory itself. This is one of the first books in this relatively young field. It is aimed at scientists, engineers and students who want to obtain a concise introduction to the state of the art in the field of cavity optomechanics. It is valuable to researchers in nano science, quantum optics, quantum information, gravitational wave detection and other cutting edge fields. Possible applications include biological sensing, frequency comb applications, silicon photonics etc. The technical content will be accessible to those who have familiarity with basic undergraduate physics.

## **Experimental Research of Cavity Optomechanics**

Zhen Shen, 2021-01-12 This thesis presents experimental research on the interaction between the optical field and the mechanical oscillator in whispering gallery mode microcavities. It demonstrates how optomechanical interactions in a microresonator can be used to achieve non magnetic non reciprocity and develop all optically controlled non reciprocal multifunctional photonic devices. The thesis also discusses the interaction between the travelling optical and mechanical whispering gallery modes paving the way for non reciprocal light storage as a coherent circulating acoustic wave with a lifetime of up to tens of microseconds. Lastly the thesis presents a high frequency phase sensitive heterodyne vibrometer operating up to 10 GHz which can be used for the high resolution non invasive mapping of the vibration patterns of acoustic devices. The results presented here show that optomechanical devices hold great potential in the field of information processing.

## **Quantum Optomechanics**

Warwick P. Bowen, Gerard J. Milburn, 2015-11-18 Written by leading experimentalist Warwick P. Bowen and prominent theoretician Gerard J. Milburn. Quantum Optomechanics discusses modern developments in this novel field from experimental and theoretical standpoints. The authors share their insight on a range of important topics including

optomechanical cooling and entanglement, quantum limits on *Cavity Optomechanics in the Quantum Regime* Thierry Claude Marc Botter, 2013 An exciting scientific goal common to many fields of research is the development of ever larger physical systems operating in the quantum regime. Relevant to this dissertation is the objective of preparing and observing a mechanical object in its motional quantum ground state. In order to sense the object's zero point motion the probe itself must have quantum limited sensitivity. Cavity optomechanics, the interactions between light and a mechanical object inside an optical cavity provides an elegant means to achieve the quantum regime. In this dissertation I provide context to the successful cavity based optical detection of the quantum ground state motion of atoms based mechanical elements. mechanical elements consisting of the collective center of mass CM motion of ultracold atomic ensembles and prepared inside a high finesse Fabry-Pérot cavity were dispersively probed with an average intracavity photon number as small as 0.1

I first show that cavity optomechanics emerges from the theory of cavity quantum electrodynamics when one takes into account the CM motion of one or many atoms within the cavity and provide a simple theoretical framework to model optomechanical interactions I then outline details regarding the apparatus and the experimental methods employed highlighting certain fundamental aspects of optical detection along the way Finally I describe background information both theoretical and experimental to two published results on quantum cavity optomechanics that form the backbone of this dissertation The first publication shows the observation of zero point collective motion of several thousand atoms and quantum limited measurement backaction on that observed motion The second publication demonstrates that an array of near ground state collective atomic oscillators can be simultaneously prepared and probed and that the motional state of one oscillator can be selectively addressed while preserving the near zero point motion of neighboring oscillators

## **Quantum**

**Optomechanics and Nanomechanics** Pierre-Francois Cohadon,Jack Harris,Leticia Cugliandolo,Florian Marquardt,2020

This book fully covers all aspects historical theoretical and experimental of the fields of quantum optomechanics and nanomechanics These are essential parts of modern physics research and relate to gravitational wave detection the subject of the Physics Nobel Prize 2017 and quantum information

## **Cavity Optomechanics with Optically Trapped Particles** Pau

Mestres Junqué,2018 Optical trapping and manipulation have emerged as powerful tools to investigate single microscopic objects in a controlled environment Using the momentum carried by light forces can be exerted to confine and manipulate objects in a wide range of conditions ranging from liquid environments to high vacuum In this thesis I implement different optical manipulation schemes to trap nano objects and coupled them to optical cavities giving rise to a cavity optomechanical interaction between the trapped object and the cavity mediated by the light s radiation pressure In a first experiment I implement a mobile optical tweezer MobOT with nanometer precision to place a levitated silica nanosphere at the standing wave of a high Finesse Fabry Perot cavity aiming to cool its center of mass motion to the ground state at room temperature To attain this goal I design a two step cooling process that starts with a parametrical modulation of the optical trapping potential which pre cools the center of mass motion along the three axis Then driving the cavity with a red detuned laser furthers cool the particle motion along the cavity axis via the optomechanical interaction To monitor the particle motion in the optical trap I implement a highly robust and sensitive detection scheme that collects the trap forward scattered field and sends it to a set of three balanced photodiodes According to a semiclassical model I present this approach can resolve the nanoparticle motion down to a single phonon excitation provided a shot noise limited balance detector I also study the use of plasmonic nanoapertures as a novel optomechanical system that increases by 10 8 the single photon optomechanical coupling strength between the trapped nanoparticle and the cavity These experiments are performed in the overdamped regime and result into a large optomechanical interaction that allows direct measurement of dynamical modulation of the trapping potential due to the motion of the trapped object Different detuning regimes are studied aiming to improve the

optical trapping performances at low laser intensities These findings are supported by finite element simulations Finally I have also made use of optical traps to perform non equilibrium thermodynamic processes with an optically trapped microparticle in a virtual thermal bath The virtual bath consists of an electrical white noise force The agreement between the temperatures obtained from equilibrium and non equilibrium measurements demonstrates the accuracy of this method Supported by theory and simulations our experiments highlight the importance of properly choosing the sampling rate and noise bandwidth for the validity of the method We apply this technique to study non equilibrium isothermal compression expansion cycles at different temperatures ranging from room temperature to 3000K We calculate some thermodynamic functionals for these processes such as work heat and entropy We show that work distributions verify the Crooks fluctuation theorem and that they fit well to a generalized Gamma Function

*Cavity Optomechanics at Millikelvin Temperatures* Sean Michael Meenehan, California Institute of Technology, Division of Engineering and Applied Science, 2015 The field of cavity optomechanics which concerns the coupling of a mechanical object's motion to the electromagnetic field of a high finesse cavity allows for exquisitely sensitive measurements of mechanical motion from large scale gravitational wave detection to microscale accelerometers Moreover it provides a potential means to control and engineer the state of a macroscopic mechanical object at the quantum level provided one can realize sufficiently strong interaction strengths relative to the ambient thermal noise Recent experiments utilizing the optomechanical interaction to cool mechanical resonators to their motional quantum ground state allow for a variety of quantum engineering applications including preparation of non classical mechanical states and coherent optical to microwave conversion Optomechanical crystals OMCs in which bandgaps for both optical and mechanical waves can be introduced through patterning of a material provide one particularly attractive means for realizing strong interactions between high frequency mechanical resonators and near infrared light Beyond the usual paradigm of cavity optomechanics involving isolated single mechanical elements OMCs can also be fashioned into planar circuits for photons and phonons and arrays of optomechanical elements can be interconnected via optical and acoustic waveguides Such coupled OMC arrays have been proposed as a way to realize quantum optomechanical memories nanomechanical circuits for continuous variable quantum information processing and phononic quantum networks and as a platform for engineering and studying quantum many body physics of optomechanical meta materials However while ground state occupancies that is average phonon occupancies less than one have been achieved in OMC cavities utilizing laser cooling techniques parasitic absorption and the concomitant degradation of the mechanical quality factor fundamentally limit this approach On the other hand the high mechanical frequency of these systems allows for the possibility of using a dilution refrigerator to simultaneously achieve low thermal occupancy and long mechanical coherence time by passively cooling the device to the millikelvin regime This thesis describes efforts to realize the measurement of OMC cavities inside a dilution refrigerator including the development of fridge compatible optical coupling schemes and the characterization of the heating

dynamics of the mechanical resonator at sub kelvin temperatures We will begin by summarizing the theoretical framework used to describe cavity optomechanical systems as well as a handful of the quantum applications envisioned for such devices Then we will present background on the design of the nanobeam OMC cavities used for this work along with details of the design and characterization of tapered fiber couplers for optical coupling inside the fridge Finally we will present measurements of the devices at fridge base temperatures of  $T_f$  10 mK using both heterodyne spectroscopy and time resolved sideband photon counting as well as detailed analysis of the prospects for future quantum applications based on the observed optically induced heating

*Probing Two-Dimensional Quantum Fluids with Cavity Optomechanics* Yauhen Sachkou,2020-07-17 Superfluid helium is a quantum liquid that exhibits a range of counter intuitive phenomena such as frictionless flow Quantized vortices are a particularly important feature of superfluid helium and all superfluids characterized by a circulation that can only take prescribed integer values However the strong interactions between atoms in superfluid helium prohibit quantitative theory of vortex behaviour Experiments have similarly not been able to observe coherent vortex dynamics This thesis resolves this challenge bringing microphotonic techniques to bear on two dimensional superfluid helium observing coherent vortex dynamics for the first time and achieving this on a silicon chip This represents a major scientific contribution as it opens the door not only to providing a better understanding of this esoteric quantum state of matter but also to building new quantum technologies based upon it and to understanding the dynamics of astrophysical superfluids such as those thought to exist in the core of neutron stars

Nonlinear Optics and Wavelength Translation Via Cavity-optomechanics Jeffrey Thomas Hill,2013 The field of cavity optomechanics explores the interaction of light with sound in an ever increasing array of devices This interaction allows the mechanical system to be both sensed and controlled by the optical system opening up a wide variety of experiments including the cooling of the mechanical resonator to its quantum mechanical ground state and the squeezing of the optical field upon interaction with the mechanical resonator to name two In this work we explore two very different systems with different types of optomechanical coupling The first system consists of two microdisk optical resonators stacked on top of each other and separated by a very small slot The interaction of the disks causes their optical resonance frequencies to be extremely sensitive to the gap between the disks By careful control of the gap between the disks the optomechanical coupling can be made to be quadratic to first order which is uncommon in optomechanical systems With this quadratic coupling the light field is now sensitive to the energy of the mechanical resonator and can directly control the potential energy trapping the mechanical motion This ability to directly control the spring constant without modifying the energy of the mechanical system unlike in linear optomechanical coupling is explored Next the bulk of this thesis deals with a high mechanical frequency optomechanical crystal which is used to coherently convert photons between different frequencies This is accomplished via the engineered linear optomechanical coupling in these devices Both classical and quantum systems utilize the interaction of light and matter across a wide range of energies

These systems are often not naturally compatible with one another and require a means of converting photons of dissimilar wavelengths to combine and exploit their different strengths. Here we theoretically propose and experimentally demonstrate coherent wavelength conversion of optical photons using photon phonon translation in a cavity optomechanical system. For an engineered silicon optomechanical crystal nanocavity supporting a 4 GHz localized phonon mode optical signals in a 1.5 MHz bandwidth are coherently converted over a 11.2 THz frequency span between one cavity mode at wavelength 1460 nm and a second cavity mode at 1545 nm with a 93% internal 2% external peak efficiency. The thermal and quantum limiting noise involved in the conversion process is also analyzed and in terms of an equivalent photon number signal level are found to correspond to an internal noise level of only 6 and 4 times  $10 \times 3$  quanta respectively. We begin by developing the requisite theoretical background to describe the system. A significant amount of time is then spent describing the fabrication of these silicon nanobeams with an emphasis on understanding the specifics and motivation. The experimental demonstration of wavelength conversion is then described and analyzed. It is determined that the method of getting photons into the cavity and collected from the cavity is a fundamental limiting factor in the overall efficiency. Finally a new coupling scheme is designed, fabricated and tested that provides a means of coupling greater than 90% of photons into and out of the cavity addressing one of the largest obstacles with the initial wavelength conversion experiment. *Generalized Optomechanics and Its Applications* Jin-Jin Li, Ka-Di Zhu, 2013. A mechanical oscillator coupled to the optical field in a cavity is a typical cavity optomechanical system. In our textbook we prepare to introduce the quantum optical properties of optomechanical system i.e. linear and nonlinear effects. Some quantum optical devices based on optomechanical system are also presented in the monograph such as the Kerr modulator quantum optical transistor optomechanical mass sensor and so on. But most importantly we extend the idea of typical optomechanical system to coupled mechanical resonator system and demonstrate that the combined two level structure and resonator system can serve as a generalized optomechanical system. The quantum optical properties which exist in typical system are also presented in the combined two level structure and resonator system.

**Nano- and Micromechanical Resonators Interacting with Light** Hayden Hewitt, 2014-12-18 Nanotechnology nanotech is the manipulation of matter on an atomic molecular and supramolecular scale. The earliest widespread description of nanotechnology referred to the particular technological goal of precisely manipulating atoms and molecules for fabrication of macroscale products also now referred to as molecular nanotechnology. A more generalized description of nanotechnology was subsequently established by the National Nanotechnology Initiative which defines nanotechnology as the manipulation of matter with at least one dimension sized from 1 to 100 nanometers. This definition reflects the fact that quantum mechanical effects are important at this quantum realm scale and so the definition shifted from a particular technological goal to a research category inclusive of all types of research and technologies that deal with the special properties of matter that occur below the given size threshold. It is therefore common to see the plural form nanotechnologies as well as nanoscale

technologies to refer to the broad range of research and applications whose common trait is size. Because of the variety of potential applications including industrial and military governments have invested billions of dollars in nanotechnology research. Through its National Nanotechnology Initiative the USA has invested 3.7 billion dollars. The European Union has invested when 1.2 billion and Japan 750 million dollars.

### **Cavity Optomechanics and Optical Frequency Comb**

**Generation with Silica Whispering-Gallery-Mode Microresonators** Albert Schließer, 2009    **Cavity Optomechanics with Nm-thick Membranes** Anna Naomi Pearson, 2020    **Quantum Measurement with Atomic Cavity**

**Optomechanics** Sydney Frances Schreppler, 2016 A cloud of ultracold atoms trapped within the confines of a high finesse optical cavity shakes from the pressure of the light that probes it. This form of measurement backaction a central component of quantum measurement theory is the subject of this dissertation. Enlisting the collective motion of ultracold atoms as the mechanical degree of freedom in a cavity optomechanical system we reach settings cold and quiet enough to allow for the effects of measurement backaction to manifest. We report predictions for and experimental observations of the Standard Quantum Limit for force sensitivity optical ponderomotive squeezing and the possibility of complex squeezing through generalized optical correlations.    **Cavity Quantum Optomechanics with Ultracold Atoms** Kater Whitney Murch, 2008

*Cavity Optomechanics with Cascaded Microtoroidal Optical Resonators* Yuanfang Zhang, 2012 In this thesis a system including one optical fibre and one microtoroid system is first inspected. This system provides us a so called resolved sideband RSB cooling mechanism which can cool the phonon number of a resonator to be lower than unit. We deduce the master equation via adiabatic elimination and evaluating the spectrum of this system by using master equation and Langevin equation. Then based on this system and its cooling mechanism a system consisting of one optical fibre and two microtoroids is explored. We consider two cases. The first is called one way driving system because there is one input field travelling in the fibre. The second is called two way driving system in which an additional input field comes from the opposite direction in the fibre. In one way driving system two microtoroids are correlated by laser light. Small fractions of laser light are sent from the fibre into toroids to form clockwise propagating optical cavity modes. The optical cavity mode is coupled to the mechanical toroid mode via radiation pressure force. For the optical cavity mode in the first second toroid a blue red resonant frequency detuning is turned by amount of the frequency of the mechanical mode which invokes a significantly effective heating cooling process. We conduct our investigation under two regimes. First the frequency of the mechanical mode is much larger than the decay rate of the cavity mode and they are both much greater than the damping rate of the mechanical mode. Second the heating cooling rates induced by the laser detuning is much larger than the damping rate of the mechanical mode. In the interesting regimes the reduced master equation describing the two correlated microtoroids is applied to investigate how an EPR type entanglement between them can be created. It is concluded small initial phonon numbers of the toroids low dissipation rates of mechanical modes and high laser induced rates can lead the system to be close to perfect correlation. We

desire the frequency of the mechanical mode to be greater than the decay rate of optical cavity mode as much as possible In two way driving system because of the extra input field there is an additional counterclockwise propagating optical cavity field in each toroid The field is also detuned as for the clockwise optical cavity modes and similarly give rise to heating and cooling effects respectively in the two toroids An additional condition that the rates induced by the extra detuned laser should be as small as possible is required By Langevin equation we can compute the equations of motion of optical cavity modes and furthermore obtain a expression for the output field of a system We find the output fields of the two systems are both in terms of mechanical modes of toroids and input fields This suggests we can combine master equation and Langevin equation to evaluate the spectra of them To attain a state close to EPR entanglement extremely low initial thermal phonon numbers of toroids are necessary Before performing entangling operation by applying resolved sideband cooling scheme for the one way driving system theoretically it is possible to cool both phonon numbers of toroids to be less than unit But it needs a longer period to cool the second one And the dissipation rate of the mechanical mode may be required to be even lower

**2D Materials for Cavity Optomechanics** Ralf Messmer,2020      Cavity Optomechanics with High-stress Silicon Nitride Films Dalziel Joseph Wilson,2012      **Nonlinear Quantum Effects and Squeezing in Cavity Optomechanics**,2015      **Cavity Optomechanics with Silica Toroidal Microresonators Down to Low Phonon Occupancy** Rémi Rivière,2011

## Embracing the Song of Term: An Psychological Symphony within **Cavity Optomechanics** **Cavity Optomechanics**

In a world eaten by displays and the ceaseless chatter of fast interaction, the melodic splendor and mental symphony developed by the published word usually disappear into the backdrop, eclipsed by the relentless noise and disturbances that permeate our lives. Nevertheless, situated within the pages of **Cavity Optomechanics** **Cavity Optomechanics** a marvelous fictional treasure filled with organic emotions, lies an immersive symphony waiting to be embraced. Crafted by a wonderful composer of language, this interesting masterpiece conducts visitors on a mental trip, skillfully unraveling the hidden melodies and profound affect resonating within each carefully crafted phrase. Within the depths with this touching review, we can examine the book is key harmonies, analyze its enthralling writing type, and submit ourselves to the profound resonance that echoes in the depths of readers souls.

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