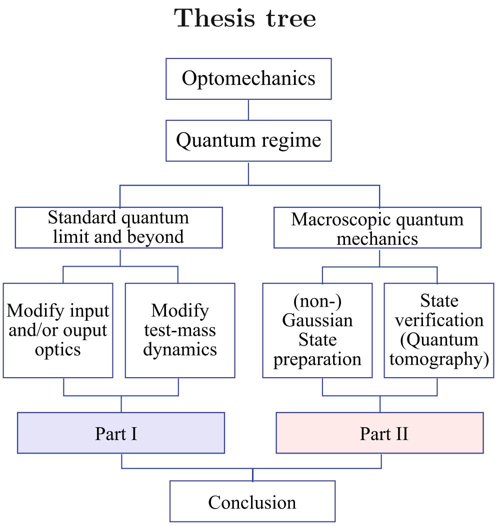
Preface

Recent significant achievements in fabricating low-loss optical and mechanical elements have aroused intensive interest in optomechanical devices which couple optical fields to mechanical oscillators, e.g., in laser interferometer gravitationalwave (GW) detectors. Not only can such devices be used as sensitive probes for weak forces and tiny displacements, but they also lead to the possibilities of investigating quantum behaviors of macroscopic mechanical oscillators, both of which are the main topics of this thesis. They can shed light on improving the sensitivity of quantum-limited measurement, and on understanding the quantumto-classical transition.

This thesis summarizes and puts into perspective several research projects that I worked on together with the UWA group and the LIGO Macroscopic Quantum Mechanics (MQM) discussion group. In the first part of this thesis, we will discuss different approaches for surpassing the standard quantum limit for the displacement sensitivity of optomechanical devices, mostly in the context of GW detectors. They include: (1) *Modifying the input optics.* We consider filtering two frequency-independent squeezed light beams through a tuned resonant cavity to obtain an appropriate frequency dependence, which can be used to reduce the measurement noise of the GW detector over the entire detection band; (2) *Modifying the output optics.* We study a time-domain variational readout scheme which measures the conserved dynamical quantity of a mechanical oscillator: the mechanical quadrature. This evades the measurement-induced back action and achieves a sensitivity limited only by the shot noise. This scheme is useful for improving the sensitivity of signal-recycled GW detectors, provided the signalrecycling cavity is detuned, and the optical spring effect is strong enough to shift the test-mass pendulum frequency from 1 Hz up to the detection band around 100 Hz; (3) *Modifying the dynamics.* We explore frequency dependence in double optical springs in order to cancel the positive inertia of the test mass, which can significantly enhance the mechanical response and allow us to surpass the SQL over a broad frequency band.

In the second part of this thesis, two essential procedures for an MQM experiment with optomechanical devices are considered: (1) *state preparation*, in which we prepare a mechanical oscillator in specific quantum states. We study the preparations of both Gaussian and non-Gaussian quantum states, and also the creation of quantum entanglements between the mechanical oscillator and the optical field. Specifically, for the Gaussian quantum states, e.g., the quantum ground state, we consider the use of passive cooling and optimal feedback control in cavity-assisted schemes. For non-Gaussian quantum states, we introduce the idea of coherently transferring quantum states from the optical field to the mechanical oscillator. For the quantum entanglement, we consider the entanglement between the mechanical oscillator and the finite degrees-of-freedom cavity modes, and also the infinite degrees-of-freedom continuum optical mode. (2) *state verification*, in which we probe and verify the prepared quantum states. A similar time-dependent homodyne detection method as discussed in the first part is implemented to evade the back action, which allows us to achieve a verification accuracy that is below the Heisenberg limit. The experimental requirements and feasibilities of these two procedures are considered in both small-scale cavity-assisted optomechanical devices, and in large-scale advanced GW detectors.



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