Abstract

This dissertation presents a study on the ultra-stable optical resonators and its applications. The main results of this work consist of the design of a room-temperature ultra-stable optical cavity along with thermal shielding and vacuum housings, a study of the fundamental theoretical performance limits and the application of the ultra-stable cavities for high-frequency gravitational wave detection and low-frequency quantum space-time fluctuation. Additionally, theoretical work is conducted to enhance the sensitivity of these cavities.

The stability of ultra-stable cavities is examined in depth, with a focus on thermal noise sources such as Brownian, thermoelastic, and thermo-optic noise. To achieve the calculated stability, the cavity spacer and housing enclosure were carefully designed to minimize sensitivity to external disturbances. The designed cavity is equipped with novel AlGaAs/GaAs crystalline mirror coatings, which are expected to improve the overall stability of the cavity compared to dielectric coatings.

We propose an ultra-stable cavity as a resonant gravitational wave detector. Using the mechanical resonance of the spacer cavity may allow for the detection of gravitational waves whose frequency matches the resonant frequency of the spacer. The strain sensitivity is enhanced by increasing the spacer mass, lowering the temperature, and expanding the beam spot size on the mirror using convex-concave mirrors to improve sensitivity to gravitational wave radiation. The ultra-stable cavity detector is mainly designed to observe frequencies beyond the current range of existing interferometers. This also is the range beyond the classical gravitational radiation sources but allows the observation of non-classical objects, such as black holes with masses less than 1 $M_{\odot}$, often called primordial black holes. Moreover, a positive observation in the high frequencies could prove the existence of sources beyond standard models, such as axions and axion-like particles.

The second proposed application of ultra-stable cavities for fundamental physics enhances the constraints on space-time fluctuations in the so-called space-time "foam" model. This work proposes improving existing limits using a set of two cavities aligned perpendicularly and parallelly, improving the previous constraints by at least an order of magnitude. Moreover, the novel approach includes two methods of using a single cavity to set a limit for the space-time fluctuations, i.e., the single cavity signal from the three-cornered hat method and the single cavity signal from the comparison with strontium atoms. Both methods establish more stringent limits on space-time fluctuations compared to previous results.