Thermal noise and radiation pressure effects in interferometric measurements

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Observation of gravitational waves has become an important challenge and several projects of interferometers are now under construction. These detectors are based on very sensitive laser interferometry to measure the relative motions of mirrors placed at the ends of two perpendicular arms. A gravitational wave would produce a differential change of the arms lengths, with a relative variation less than 10^{-21} for gravitational-wave frequencies between 10 Hz and 1 kHz. There are thus many noise sources which can affect the sensitivity of gravitational-wave detectors and a great effort has been done to reduce these noises. For example, effects of ground motion are filtered by suspending the mirrors to very complex super-attenuator devices. The sensitivity is now mainly limited by the thermal noise of the mirrors at low frequencies, and by the photon noise of the laser beam at higher frequencies.

The Brownian motion of the mirrors can be decomposed into suspension and internal thermal noises. The former corresponds to the motion of the center of mass of the mirror induced by the thermal excitation of the pendulum suspension. The latter is due to thermally induced deformations of the mirror surfaces. It constitutes the main limitation in the intermediate frequency domain. Experimental observation of this noise is of particular interest since its effect strongly depends on the spatial matching between light and internal acoustic modes of the mirror. It also depends on the mechanical dissipation mechanisms which are not well known in solids.

Observation and control of this Brownian motion is thus an important issue for very sensitive interferometric measurements. Mirror displacements induced by thermal noise are however very small, on the order of $10^{-19}\ m/\sqrt{Hz}$ at room temperature. This corresponds to displacements of a billionth of an Angstrom for an analysis frequency bandwidth of 1 Hz. Very sensitive displacement sensors have thus to be developed, and one promising technique consists in optical transducers based on a high-finesse Fabry-Perot cavity. Near an optical resonance, the phase of the beam reflected by a single-ended cavity strongly depends on the cavity length, and then on the mirror motion. By using a homodyne detection of the reflected field, one can expect to measure small mirror displacements with a sensitivity only limited by the shot-noise of the light beam.

Another interest of the measurement of small displacements is the study of quantum effects of radiation pressure. When a movable mirror is exposed to a laser beam, its motion is coupled to the laser intensity via radiation pressure. This optomechanical coupling plays an important role in interferometric measurements since it induces a *Standard Quantum Limit* of the sensitivity. This quantum effect can be studied by using a single-port high-finesse cavity with a movable mirror for which the effects of the mirror motion are enhanced by the cavity finesse. Such a device has other interesting quantum properties since it can be used to generate squeezed states of light or to perform a quantum nondemolition measurement of the intensity of light [1].

We are doing an experiment based on a compact optical cavity. One mirror is coated on the plane side of a small plano-convex mechanical resonator made of fused silica. This resonator is designed for the observation of quantum effects of radiation pressure since it has high mechanical resonance frequencies and a small effective mass [2]. The phase of the field reflected by the cavity is measured by a homodyne detection with a high quantum efficiency.

We have observed the internal thermal noise of the mirror, both near the fondamental resonance frequency of the resonator, and at lower frequencies [3]. At resonance, the thermal spectrum has a lorentzian shape, as expected from the fluctuation-dissipation theorem. The minimum observable displacement corresponds to the shot-noise limit and is large enough to observe the background thermal noise of the mirror at low frequency.

We have also cooled the mirror by the radiation pressure of light [4]. A feedback mechanism controls the Brownian motion via the intensity modulation of a laser beam reflected on the mirror. We have reduced the thermal noise by a factor 20 and the effective temperature by a factor larger than 10, both at the mechanical resonance frequency and at low frequency. We have shown that at resonance this cooling mechanism corresponds to a cold damping process. We have studied the mechanical response of the mirror to an external force in presence of feedback. The results obtained show that the radiation pressure exerted by the light corresponds to a viscous force without any additional thermal noise.

We have also studied the transient evolution of the thermal noise when the cooling mechanism is applied or stopped. We have shown that the relaxation time towards the cooled regime can be much shorter than the relaxation time towards the thermal equilibrium. We have finally examined the possible application of this cooling mechanism to control the thermal noise in a gravitational-wave interferometer.

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