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Ultra-low dissipation resonators for improving the sensitivity of gravitational wave detectors

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ABSTRACT

Broadband enhancement of the sensitivity of gravitational wave detectors can be achieved by the use of negative dispersion filters to create white light signal recycling cavities. This filter should have mechanical frequency of 300 kHz or higher and $T/Q_{\mathrm{m}} \sim 6 \times 10^{-10}$ K, in order to achieve appreciable sensitivity enhancement in the range of 1–2 kHz. This paper investigates the possibility of using optical dilution of GaAs/AlGaAs-coated Si and GaAs “cat-flap” micro-resonators to achieve such performance. We analyse the loss contributions to such resonators, particularly thermoelastic loss, suspension loss and acceleration loss. Sufficient reduction of thermoelastic loss is possible when operating near the zero thermal expansion point with temperature control of ∼1 K for both materials. Acceleration loss and suspension losses can be minimised in the frequency range 10^4–10^5 Hz, allowing Q-factors in the range 10^{11}–10^{12}, but these are reduced at the target 400 kHz frequency. Results are subject to assumptions regarding material losses. Fabrication techniques for creating GaAs and SiN_x suspended silicon cat-flap resonators are presented.

Preamble

Vladimir Braginsky’s work had enormous impact on research at the University of Western Australia, particularly in relation to developing and creating ultralow noise systems with low dissipation that exhibited ultralow noise. In 1975, at a conference in Erice, Sicily, Braginsky had shocked the community by emphasising that the standard quantum limit would set an ultimate limitation of sensitivity for cryogenic resonant bar detectors.

Blair was proposing the use of niobium for a proposed new cryogenic resonant bar detector in Australia, because of the observed high quality factor, $\sim 6 \times 10^7$ he had recently observed in a magnetically levitated niobium bar at Louisiana State University. Braginsky proposed the possibility of using superconducting microwave re-entrant cavities to create parametric transducers for the niobium detector. This suggestion was adopted by the group at UWA. This led, within a few years, to successful demonstration of superconducting reentrant cavities, and then to a non-contacting microwave cavity measurement of a small levitated niobium bar, that at the time was the lowest noise temperature observed in a mechanical measurement [1].

However, this measurement exposed a new technical issue: that any cavity measurement of position requires extreme frequency stability for the pump oscillator. Braginsky again proposed a solution: the use of whispering gallery modes in a sapphire dielectric resonator. The UWA group again adopted Braginsky’s suggestion.

Experiments quickly exposed some limitations in the use of dielectric resonators associated with radiation losses [2]. This led to the invention at UWA of the concept of the sapphire loaded superconducting cavity, which was demonstrated in a succession of experiments [3]. Ultimately oscillators based on this technology became known as the sapphire clock. They were shown to achieve extremely low phase noise, and the technology spawned an industry devoted to ultralow phase noise oscillators.

The combination of niobium bar with re-entrant cavity and sapphire oscillator allowed the creation of the gravitational wave detector NIOBE with very low noise temperature [4]. In Moscow Braginsky had explored radio frequency cavity measurements of torsion balances and had observed and analysed the opto-mechanical interaction in such systems. Braginsky’s work had revealed the possibility of negative damping and negative springs associated with parametric interactions. These phenomena were observed and harnessed in the detector NIOBE. Parametric self damping or “cooling” was used to enable the detector to be operated without inconveniently high quality factor. Simultaneously the phenomenon of

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parametric instability associated with large negative damping was observed.

Laser interferometer gravitational wave detectors make use of optical cavities, and are similarly dependent on the use of a low phase noise frequency measurement. They are similarly sensitive to electromechanical phenomena involving negative damping and negative springs. Braginsky used his deep understanding of electromechanical interactions to predict the phenomenon of three mode parametric instability [5]. His work inspired the UWA group to research this phenomenon, which led to the detailed prediction of parametric instability in Advanced LIGO by Zhao et al. [6] and to numerous exploring this phenomenon, including the first observation of this phenomenon in an optical cavity [7], the first observation in a long suspended cavity [8] and finally the observation of this phenomenon in Advanced LIGO that proved the predictions made 10 years earlier [9].

The following paper is about an extreme application of electromechanical interactions, and the possibility of creating optomechanical resonators that use the properties of optomechanical interactions to achieve quite unprecedented devices: catflap resonators in which the vast majority of the restoring forces are created by light, and in which special tuning of the optomechanical interaction leads to the creation of a cavity with negative optical dispersion. If this technology can be realised it will allow white light cavities to be created in which all frequencies within a certain bandwidth are simultaneously enhanced.

The catflap optomechanical cavity would break the nexus between resonant gain and bandwidth, allowing high resonant gain to occur across a large bandwidth. The work is built on a legacy of work inspired by Braginsky.

Braginsky's work was not undertaken alone. He attracted and inspired an outstanding team of coworkers. This paper is dedicated to Braginsky's memory, and to his coworkers whose efforts were essential in the creation of the huge body of experimental and theoretical research with whom his name is associated.

Introduction

The first detection of gravitational waves (GW) in 2015 [10,11] was a historic moment in precision measurement and noise reduction. The 4 km long detectors use extremely high laser powers to detect strains of less than 10^{-20} in the perpendicular arms. The waves were calculated to have been emitted from binary black hole sources more than 1 billion light years away from earth. Bringing the sensitivity of the interferometers down to the level to be able to measure these waves has required considerable reduction of seismic noise, thermal noise in both suspension and test mass internal modes, as well as shot noise.

Many advanced technologies are used in the Advanced LIGO detector to reduce the thermal noise of the suspension and test masses. Multi-stage spring-mass system reduce the coupling to seismic noise. Fused silica test masses have very low thermal expansion and low thermal noise. The work of Braginsky and colleagues was instrumental in reducing the noise of the suspension, with the implementation of high quality factor high stress fused silica suspending wires [12,13]. Braginsky and colleagues also showed that by increasing the Q-factor of the mechanical modes of the suspension, it would be possible to reduce the thermal noise contribution [13,14] via the fluctuation–dissipation theorem. With the advancements in the suspension and test mass, the limiting noise source is now thermal and Brownian noise of the optical coating. The thermal noise of the coating is related to the thermal fluctuation of the expansion coefficient [15] and refractive index [16].

The event rate of gravitational waves scales with the detection volume, which is proportional to the cube of the detection radius. Thus, small improvements in sensitivity can lead to large increases in the detection rate, allowing detailed statistical characterisation of binary black hole mergers that generate gravitational waves.

Currently, GW detectors use dual recycling to either tune to a particular frequency of interest, or set broadband enhancement. However, there is a trade-off between resonant enhancement and bandwidth enhancement. This paper addresses a means for improving the bandwidth of detectors by using white light cavities.

The use of a white light cavity with broadband resonance [17–19] was proposed to improve the GW detector sensitivity. This cavity requires a negative dispersion filter in the signal recycling cavity that can cancel the propagation phase delay of the signal induced in the interferometer by an incoming gravitational wave. However, in order to keep the thermal noise below the quantum noise, the filter requires a mechanical resonator with a quality factor dictated by [19]:

$$8k_bT \cdot Q_m^{-1} \leq \hbar\gamma_{sr}, \tag{1}$$

where k_b is the Boltzmann constant, T is the environmental temperature of the filter cavity, Q_m is the mechanical quality factor and γ_{sr} is the unmodified bandwidth of the signal recycling cavity. This results in a $T \cdot Q_m^{-1}$ requirement of approximately 6×10^{-10} K to bring the thermal noise of the filter below quantum noise sources. Some broadband enhancement can be achieved with $T \cdot Q_m^{-1} \sim 6 \times 10^{-9}$ K. This paper specially addresses issues associated with achieving such low acoustic losses in a micro-resonator.

To achieve a very high mechanical quality factor, a "cat-flap" resonator with extreme optical dilution was proposed [20] to reduce coupling to thermal and mechanical dissipation. The cat-flap is a mirror hangs by an extremely thin membrane or nanowires. By using a radiation pressure trap, it has been shown that it is possible to increase the resonant frequency of the mechanical resonator such that more than 99% of the restoring force is provided by light [21,22]. In principle, the increase in the quality factor scales with $Q_0(\omega_{opt}/\omega_0)^2$, where Q_0 is the intrinsic quality factor of the suspension material, ω_0 is the fundamental resonance of the centre-of-mass pendulum mode and ω_{opt} is the frequency of the optomechanical resonator when the optical trap is applied.

However, the increase in Q is limited by various mechanical and thermal dissipation mechanisms in the resonator. The mechanical loss in the substrate is present in the form of acceleration loss, where the acceleration of the resonator through the optical field causes deformation that couples to internal vibrational modes of the substrate. A 1-D analysis of optical trap coupling to internal modes shows that the loss contribution to the mechanical resonance, assuming that the optical trap frequency has not surpassed the internal resonance frequency, scales as [20]:

$$Q_{accel}^{-1} = Q_{int}^{-1}\left(\frac{\omega_{opt}}{\omega_{int}}\right)^2, \tag{2}$$

where Q_{int} is the quality factor of the substrate and ω_{int} is the first internal mode of vibration of the substrate. In reference [20], it is shown that the limit of acceleration loss, taking into account the ultra high vacuum gas damping, the Q-factor of a 50 μm resonator can be brought from 10^6 at 1 Hz to 10^{10} at 1 MHz. However, other losses could limit this performance.

Noise from the thermoelastic losses is a limiting factor at room temperature. Thermoelastic noise is due to the internal modes vibration in the substrate causing localised volume changes, which then produce temperature gradients and heat flow. In order to improve the thermoelastic noise characteristics, it is necessary to either adjust the dimensions to reduce the losses induced by heat flow, or construct the resonator from a material which has a zero thermal expansion coefficient at certain temperature, and operate at that temperature. For example, silicon has zero thermal expansion at 121 K [23] and 8 K [24], and gallium arsenide has zero