Dual Detector of Gravitational Waves

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Abstract

We present the concepts and recent progress on a new kind of gravitational wave detector, which we name the 'dual detector' and which would be broadband and based on resonant masses. We also report on the related selective readout, which helps in rejecting thermal and back-action contribution from non gravitational wave sensitive acoustic modes. A SiC dual detector, 2.8m in diameter and equipped with a wide area selective readout, would reach spectral strain sensitivities $\sim 1 \cdot 10^{-23}/\sqrt{Hz}$ between 1.3kHz and 4.3kHz: thus it would be complementary to 'advanced' interferometers.

1. Introduction

Gravitational wave (gw) detectors aim at measuring tiny relative strains $\delta l/l$ of test masses where $\delta l/l = h/2$ and h is the wave amplitude; for ground-based detectors a significant expected rate of the incoming signal can be achieved only if the sensitivity is pushed to $h \sim 10^{-20} \div 10^{-21}$. Basically, ground-based detectors are naturally divided into two classes: the resonant detectors and the interferometric ones. The first class aims at detection in a frequency range centered on the internal mechanical resonance of the test mass, presently a bar resonating at ∼900 Hz. The second class aims at detection in a frequency range which spans from frequencies larger than the test mass suspensions ($\sim 10 \div 50$ Hz) up to frequencies smaller than the first internal modes of the test masses themselves (a few kHz). Interferometers are widely recognized as wide-band devices, in contrast to the narrow-band acoustic detectors; interferometers could also be operated in a narrow-band regime, by peaking the sensitivity in a chosen frequency interval. While the first generation of long-baseline interferometers is just entering into the debugging and data-taking phases, plans for the second generation are already

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being prepared and the related R&D programs have started [6,7]. Also, potentially more sensitive acoustic detectors, based on spherical resonators, are being built in a worldwide network [1,5]: the frequency range of sensitivity will be about 10% of the central frequency set by the quadrupolar resonance, at a few kHz.

We have proposed a third kind of detector [4,2], which aims at detection in a frequency range, a few kHz wide, above $\sim$ 1kHz: this spectral region is of particular interest as it is that expected for signals from fully relativistic stellar sources [9]. In this paper we report the progresses on the concept and towards the definition of the feasibility of this new detector, named the 'dual detector'.

2. The dual cylinder

In the first proposal [4] the new detector was based on two nested spheres, both sensitive to the gw signal and whose differential displacement is measured by a set of optical sensors optimally distributed on the sphere surfaces: the detector was named 'dual sphere'. The main advantage of the spherical geometry is the omni-directional responsivity assured by the simmetry, once equipped with at least 5 readout channels. Recently [2], we have studied a simpler detector configuration of cylindrical simmetry, the 'dual cylinder', which offers the advantage of naturally hosting the 'selective readout' described in the following but gives up to the omni-directionality: nonetheless this is still better than that of interferometric detectors.

The idea of a dual detector is to have two concentric elastic and massive bodies in free-fall, whose quadrupolar mechanical resonances, which are eventually excited by the passing gw, are at different frequencies: the gw detection is accomplished by reading the differential deformation of the facing surfaces, while the center of mass of the system provides for the rest frame of the measurement. The basic features of a dual detector can be illustrated by a simple one-dimensional model: the detector is schematized as two independent oscillators of frequencies ν_1 and ν_2, driven by the same gw force. The latter is measured from the measurement of the relative displacement $x_1 - x_2$. The frequency region between ν_1 and ν_2 is of particular interest: here the same force drives one oscillator above and the other below resonance: therefore the displacements are out of phase and thus they sum up in a differential measurement, resulting in a signal enhancement with respect to the single oscillator response. Let us now consider the noise budget: fundamental noise sources come from the thermal noise of the oscillators and from the force and displacement noise of the amplifier used in the differential measurement. As the back-acting force noise is applied with opposite sign on the two oscillators, their response is in-phase and thus is greatly depressed by the differential measurement [2,3].

In a real detector, the simple oscillators are replaced by elastic 3-dimensional bodies, which possess a variety of acoustic modes of resonance:

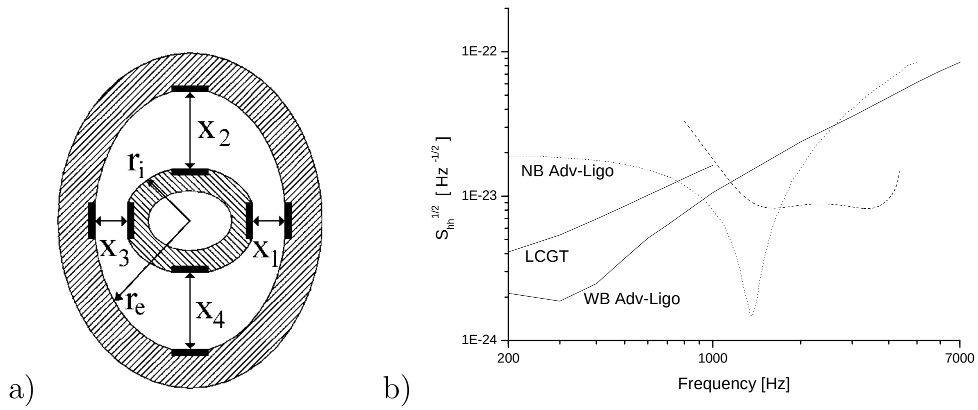

Fig. 1. a) Cross-section of the dual cylinder detector deformed by the gw signal: the area x_i, i=1,...4 are shown where the signal is averaged over. b) Expected SQL sensitivity for a SiC dual cylinder (dashed line). For comparison sensitivities predicted for LCGT and Advanced Ligo in both wide-band (WB) and narrow-band (NB; dotted line) operation are also shown.

in the limit of validity of a normal mode expansion, each mode contributes its own (thermal and back-action) noise and the detector output is affected by the sum of such terms: on the contrary, the signal is contributed only by the first few modes with quadrupolar sensitivity.

To approach the ideal 1-dimensional model which offers the signal enhancement and the back-action noise reduction described above, it is necessary to devise the measurement so not to be sensitive to the majority of these modes. This is accomplished by devising the readout that selects geometrically the modes, the so-called 'selective reading'. We refer to the system of two co-axial cylinders, which is the geometry of the proposed detector: the detector response is maximized for a gw signal that propagates parallel to the cylinder axis z. We average the differential dispacement over 4 distinct areas $x_1, ..., x_4$ and then combine them into $X_d = x_1 - x_2 + x_3 - x_4$, as shown in fig.1.-a). It can be seen that this combination accompained by large surfaces over which $x_1, ..., x_4$ are averaged gives a significant rejection to modes that do not posses the quadrupolar symmetry and thus helps in reducing the total detector noise. It should be noted that in order to measure the two basic polarization states (usually referred to as the $+$ and $\times$ polarizations) of the gw signal, two selective readouts rotated by $\pi/4$ around the z-axis are necessary.

Thanks to the selective readout, an almost flat detector response can be achieved between the quadrupolar modes of the cylinders, in spite of the large number of acoustic modes of both masses. In fact, not only the back-action noise is suppressed as described above, but also the large sensed areas guarantee thermal noise reduction as contribution from high-frequency modes averages to zero (this happens in the limit of acoustic wavelength $\leq$ sensor linear dimension). As a net result, we obtain a good convergence of the system response by adding less than 100 modes in the normal mode expansion.

A practical implementation of the selective reading can be accomplished by a capacitive readout, evolution of that employed in resonant bar gw detectors: each polarization channel would be a series of 4 capacitive transducers, gradiometically connected and sensed by a single SQUID amplifier. We are also studying the possibility of implementing an optical readout, also evolution of that under development for bar detectors: here the main problem comes from the difficulty in achieving a sensed area larger than 1cm^2, as required, but an idea on how to extend the sensed area has already appeared [8] . In both cases, Standard-Quantum-Limited (SQL) sensitivity is necessary to get satisfactory detector performance. The SQL detector sensitivity is evaluated by neglecting the thermal noise and by balancing the displacement and force noises of the amplifier. To approach the limit of negligible thermal noise, high mechanical quality factor Q materials and low temperatures are considered.

In fig.1.-b) we show the SQL sensitivity of a SiC dual cylinder, along with sensitivity from 2nd generation long-baseline interferometers (LCGT and Advanced-LIGO in both wide and narrow-band operation) which the dual cylinder can complement. The radius of the inner SiC cylinder is 0.82m while the internal/external radii of the outer SiC cylinder are respectively 0.83/1.44m; the height is 3m and the total mass amounts to 20.5 + 41.7 tons. SiC is a ceramic material which has very high cross section to the gravitational signal: it also has mechanical and thermal properties of interest here but its dissipation has not been measured at low temperatures so far. In alternative, we can consider molybdenum, which has a lower cross section but is known to reach $Q/T > 2\cdot 10^8$/K at low temperatures: a Mo detector, 1m in diameter, would reach spectral sensitivity of $\sim 3\cdot 10^{-23}/\sqrt{Hz}$ between 2kHz and 6kHz.

3. References

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