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First room temperature operation of the AURIGA optical readout

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Abstract
In the frame of the AURIGA collaboration, a readout scheme based on an optical resonant cavity has been implemented on a room temperature resonant bar detector of gravitational waves. The bar equipped with the optical readout has been operating for a few weeks and we report here the first results.

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1. Introduction

Cryogenic resonant bar detectors of gravitational waves are currently operating equipped with a capacitive or inductive transducer, using SQUID electronic preamplifiers, or with a microwave resonant cavity as a readout system for the extraction of the gravitational wave signal [1]. An alternative transduction scheme, proposed in past years [2, 3], is based on a laser interferometric technique. A Fabry–Perot optical cavity is built with one mirror attached to the bar and a second mirror attached to the resonant part of the transducer, i.e. the oscillating mass of the transducer that is resonantly coupled with the first longitudinal mode of the bar. The relative motion of the mirrors is converted into a frequency shift of the resonance frequency of the optical cavity. The frequency shift can be detected by comparison with a stable frequency reference.

A prototype of this optical readout has recently been implemented on a room temperature bar, in the framework of the AURIGA collaboration. The bar equipped with the optical readout has been operating as a gravitational wave detector for a few weeks. Here we describe the

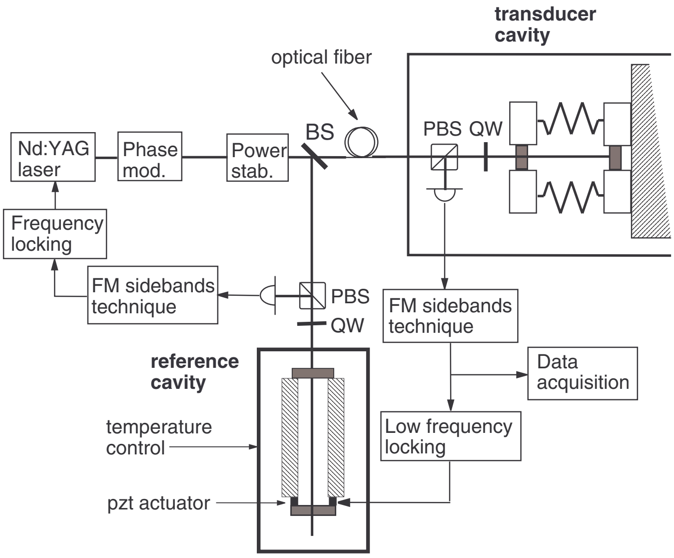

Figure 1. Scheme of the optical readout. BS: beam splitter; PBS: polarizing beam splitter; QW: quarter-wave retarding plate.

experimental setup of the optical readout and report the first results concerning the operation of the detector.

2. The optical readout

The bar is a 3 m long, 0.6 m diameter cylinder made of Al5056, whose mass is about 2300 kg. It is kept at room temperature and its first longitudinal mode resonates at $\nu_b = 875$ Hz, with a mechanical quality factor Q_b of 1.8×10^5. The bar is enclosed in a vacuum chamber and suspended by a cascade of passive mechanical filters, in order to isolate it from the floor vibration noise.

The optical readout is based on a 6 mm long Fabry–Perot cavity (which is referred to in figure 1 as the transducer cavity (TC)) formed by a couple of mirrors, one of which is fixed to one end of the bar and the other is mounted on the resonant part of the transducer. The frequency variation of the TC is detected by means of a laser, whose frequency is stabilized to that of a second, stable Fabry–Perot cavity, which we call the reference cavity (RC). The laser source is a diode-pumped Nd:YAG laser (Lightwawe 126-1064-50), emitting 50 mW at 1064 nm. As sketched in figure 1, the laser is phase modulated at 13.3 MHz by means of a resonant electro-optic modulator (EOM). The beam passes through a second EOM, which could be used to stabilize the laser power, as described elsewhere [4], even though in the present study this stabilization is not employed. The beam is divided into two parts by the beam splitter BS. The reflected beam is coupled into a single-mode, polarization-preserving optical fibre, which delivers the radiation inside the bar vacuum chamber. The fibre end is fixed to an aluminium board, placed on the top of the bar middle section, and the exiting beam is directed to the TC by using a lens doublet and two tilting mirrors mounted on the same board. On the same board there are a photodetector and an optical circulator, formed by a polarizing beam splitter followed by a quarter-wave retardation plate, which deviates the radiation reflected by the TC onto the photodetector. The beam transmitted through the BS

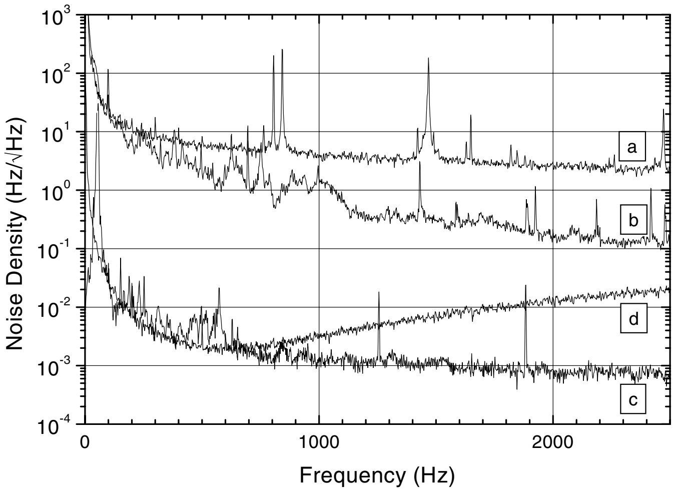

Figure 2. Frequency noise spectra: (a) noise spectrum of the detector output signal, (b) out-of-resonance noise of the signal from the TC, (c) out-of-resonance noise of the signal from the RC and (d) in-loop noise of the laser when locked to the RC.

is coupled into the RC, and the reflected beam is collected on a second photodetector. The RC is made of two mirrors separated by an Invar spacer, 10 cm long, and a ring-shaped PZT actuator, 1 cm long, which allows length tuning of the cavity. The cavity is enclosed in a vacuum chamber, whose temperature is actively stabilized within 0.1 K. The transducer and reference cavities have finesses of 28 000 and 44 000 respectively.

According to the Pound–Drever scheme [5], the ac component of signals coming from the two photodetectors is demodulated at 13.3 MHz and filtered. The resulting signals are used as discriminators for frequency locking and analysis. The laser frequency is locked to a resonance peak of the reference cavity with a servo loop which has a unit gain frequency of 30 kHz and a gain of 130 dB around 1 kHz. Then the resonance peak of the RC can be superimposed to a resonance of the TC by operating on the PZT actuator. The Pound–Drever signal coming from the TC is used to frequency lock the RC resonance to the TC. This second servo loop acts on the PZT and its bandwidth is only $\sim$10 Hz, thus the two cavities can be considered free in the frequency range where the bar detector is resonant.

3. Detector performance

Once the system of the two cavities and the laser is locked, the Pound–Drever signal from the TC is acquired, in order to extract information about the relative motion of the TC mirrors. The acquired data are analysed by the same software which is currently used for the ultracryogenic AURIGA detector, with minor changes [6]. Figure 2 shows the noise spectrum (a) of the signal from TC when the system is locked, along with the out-of-resonance noise (b) of the same signal, the out-of-resonance noise (c) of the signal from the RC, and the in-loop noise (d) of the laser when locked to the RC. The noise spectrum (a) shows the peaks at $\nu_- = 856$ Hz and $\nu_+ = 892$ Hz, due to the resonances of the coupled oscillators system formed by the bar first longitudinal mode and the transducer. A continuous background with a well defined $1/f$ behaviour is present, whose origin is still under investigation. The out-of-resonance spectrum (b) should be essentially shot noise limited, however excess amplitude noise is

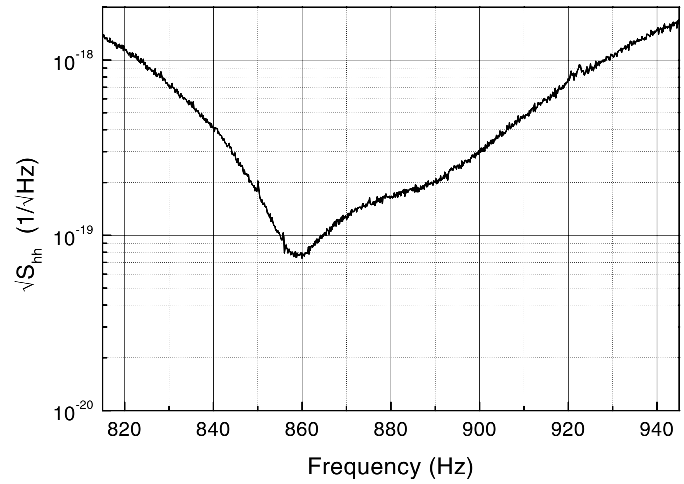

Figure 3. Strain sensitivity $\sqrt{S_{hh}}$ of the GW bar detector equipped with optical readout. The sensitivity mainly peaks in the neighbourhood of the mode (−) which has the higher Q value. The total bandwidth is ∼25 Hz.

present, especially at lower frequencies. The Q factors for the two resonances of interest have been determined by decay time measurements, with the results $Q_- = 16\,600$ and $Q_+ = 8700$.

The locking procedure is manual and it takes typically less than 10 min. The system remained locked and operating for periods of about 24 h on average, and with a maximum time of 43 h. Often the locking was turned off deliberately for diagnostic purposes, in other cases the locking failed without our intervention. There are two major factors which limit the duration of the locking of the laser and the cavities: temperature changes of the cavities and mode hoppings of the laser.

TC is not thermally stabilized and its temperature drift leads to a drift in the resonance frequency, so that the servo electronics have to correct the length of the reference cavity and the laser frequency. The laser can be tuned continuously but it suffers mode hoppings which limits the continuity of the tuning to ∼7 GHz, and when the laser approaches a mode hop the locking fails. These mode hops can also be approached if the laser itself changes its emission features due to environmental changes, e.g. the temperature of the room.

To describe the sensitivity of the detector we show in figure 3 a typical strain amplitude noise. The contribution of the mode (−) is more significant with respect to that of the mode (+), due to its higher Q. The sensitivity curve has a bandwidth of about 25 Hz, which is at least an order of magnitude larger than the value of ∼1 Hz typical of the detectors presently operating. The analysis of the acquired signal was optimized for a gravitational burst input signal and the minimum detectable relative displacement, or burst sensitivity, which can be estimated as $h_{\min} = 9 \times 10^{-17}$.

4. Thermal noise

The bar and the resonant transducer can be schematized as a system of two coupled harmonic oscillators, at least in the neighbourhood of the first longitudinal mode of the bar. A description of the system can be given in terms of the so-called normal modes, which redefine the motion of the system as that of two separate uncoupled oscillators. However, it has been observed

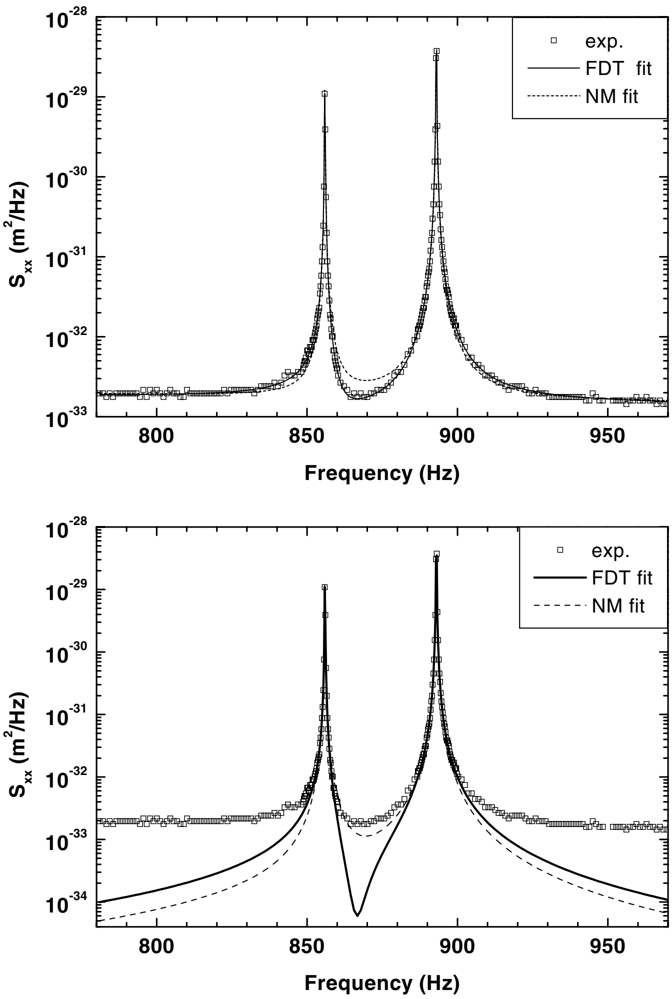

Figure 4. Top, fit of the experimental power spectral density. FDT: fluctuation–dissipation theorem. NM: normal mode expansion. Bottom, the fitted curves are plotted without the wideband $1/f$ contribution.

that this assumption fails when inhomogeneous losses occur [7], as experimentally verified in a recent work [8]. For our system the condition for the validity of the normal mode expansion can be given as $Q_b\nu_b = Q_t\nu_t$, where ν_b, ν_t, Q_b and Q_t are the frequencies and the Q factors of the bar and the transducer, respectively. The different values we measured for Q_- and Q_+, which can be explained in terms of the different values of the original Q_b and Q_t, suggest that in our case the normal mode treatment cannot describe the observed thermal noise.

In order to verify this hypothesis, we tried to fit the experimental noise power spectral density of the output signal from the detector with the prediction of the fluctuation–dissipation theorem. A background noise term was added, in order to take into account the observed $1/f$ part of the experimental noise power spectrum. From the fitting process we can retrieve Q_b, Q_t and the frequencies ν_b, ν_t of the two oscillators, and the effective mass of the transducer m_t. The effective mass of the bar is known and kept constant during the fitting process. The thermodynamic temperature was assumed to be the same for both the oscillators and equal to

Table 1. Parameters from the fit of the experimental power spectral density. The error is given in parenthesis on the last significant digit.

ν_b (Hz)	ν_t (Hz)	Q_b	Q_t	m_t (kg)
866.361 (3)	882.248 (3)	1.8×10^5 (2)	6614 (4)	1.70 (2)

the room temperature $T = 296$ K. The fitted parameters are given in table 1. The fit is not very sensitive to variations in the value of Q_b and this parameter is affected by a larger relative error compared to the other parameters. However, the value agrees well with the one measured for the bare bar. Also, we tried to fit the experimental spectrum with the prediction based on the normal mode expansion [7]. The resulting curves for both fits are plotted in figure 4, together with the experimental data. The normal mode expansion clearly fails to fit the experimental data, especially in between the two resonances.

5. Conclusions and perspectives

We present the first full operation of a readout for a gravitational wave bar detector, based on optical Fabry–Perot cavities. This optical readout has been mounted on a room temperature Al5056 bar identical to that of the AURIGA detector. This system is operating as a gravitational wave detector with a burst sensitivity $h_{\mathrm{min}} = 9 \times 10^{-17}$ and a bandwidth of about 25 Hz. These results are encouraging in view of the planned implementation of this optomechanical readout on a cryogenic bar (100 mK), for which a burst sensitivity of about 2×10^{-20} and a bandwidth of about 50 Hz are expected. For this purpose the cryogenic behaviour of the optical elements is currently under investigation.

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