

First room temperature operation of the AURIGA optical readout

M De Rosa†, L Baggio‡, M Cerdonio§||, L Conti§||, G. Galet||,
F Marin†, A Ortolan¶, G A Prodi‡, L Taffarello§,
G Vedovato||, S Vitale‡ and J P Zendri§

† INFN, Sezione di Firenze, Dipartimento di Fisica, Università di Firenze, and LENS,
Largo E. Fermi 2, I-50125 Firenze, Italy

‡ INFN Gruppo coll. di Trento, and Dipartimento di Fisica, Università di Trento,
I-38050 Povo (TN), Italy

§ INFN, Sezione di Padova, Via Marzolo 8, I-35131 Padova, Italy

|| Dipartimento di Fisica, Università di Padova, Via Marzolo 8, I-35131 Padova, Italy

¶ INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro (PD), Italy

E-mail: conti@lnl.infn.it

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 capacitive or inductive trasduced, using SQUID electronic preamplifiers, or with microwave resonant cavity as a readout system for the extraction of the gravitational wave signal [1]. An alternative trasduction scheme, proposed in the past years [2, 3], is based on a laser interferometric technique. A Fabry–Perot optical cavity is built with one mirror attached on the bar and a second mirror attached on the resonant part of the trasducer, i.e. the oscillating mass of the trasducer 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 waves detector for a few

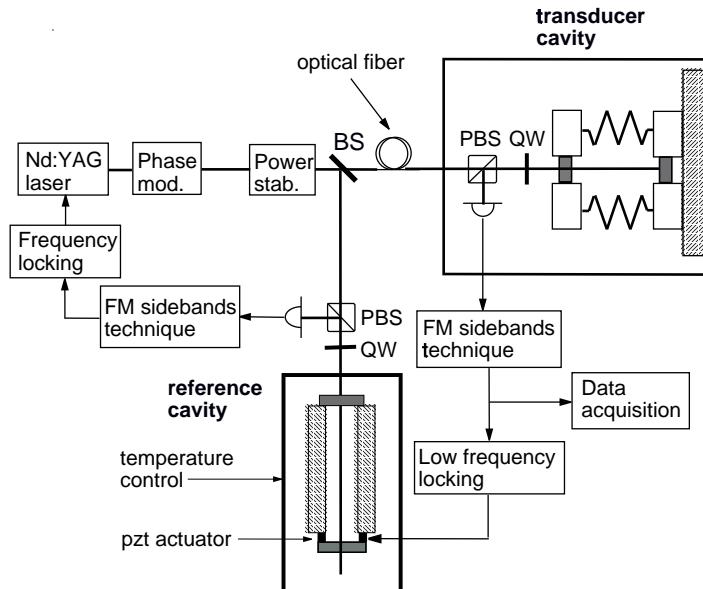


Figure 1. Scheme of the optical readout. BS: beam splitter; PBS: polarizing beam splitter; QW: quarter-wave retarding plate.

weeks. Here we describe the 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 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 Fabry-Perot cavity (which is referred on Fig. 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 trasducer. 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 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 Fig. 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 work this stabilization is not employed. The beam is divided in two parts by the beam splitter BS. The reflected beam is coupled into a single-mode, polarization-preserving optical fiber, which delivers the radiation inside the bar vacuum chamber. The fiber end is fixed on an aluminium board, placed on the

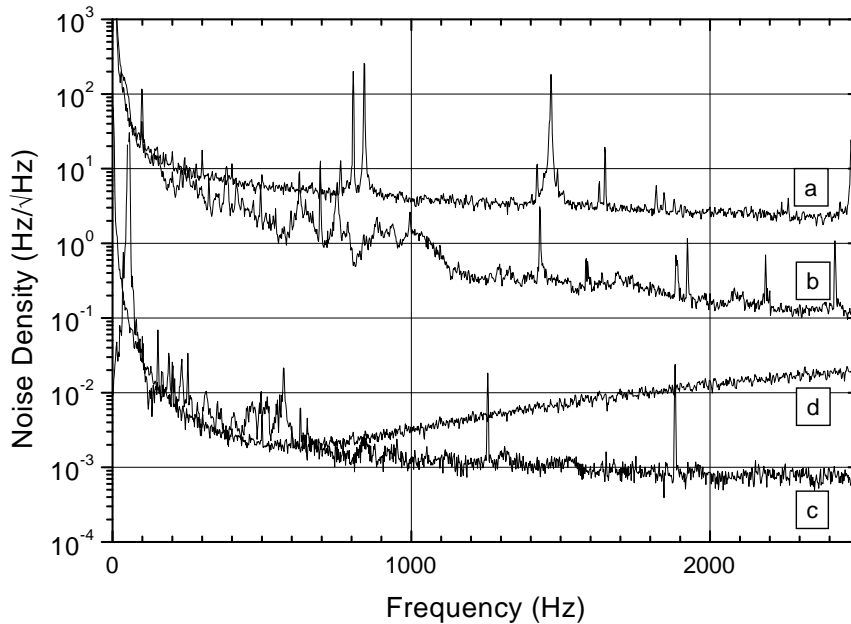


Figure 2. Frequency noise spectra. a) noise spectrum of the detector output signal; b) out-of-resonance noise of the signal from the TC; c) out-of-resonance noise of the signal from the RC; d) in-loop noise of the laser when locked to the RC.

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 the optical circulator, formed by a polarizing beam splitter followed by a quarter-wave retardation plate, which deviates the radiation reflected by the TC on the photodetector. The beam transmitted through BS is coupled into the RC, and the reflected beam is collected on a second photodetector. The RC is made by two mirrors separated by an Invar spacer, 10 cm long, and a ring-shaped PZT actuator, 1 cm long, which allows the length tuning of the cavity. The cavity is enclosed in a vacuum chamber, whose temperature is actively stabilized within 0.1 K. Transducer and reference cavities have finesse of 28000 and 44000 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 discriminator 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 ~ 10 Hz, thus the two cavities can be considered free in the frequency range where the bar detector is resonant.

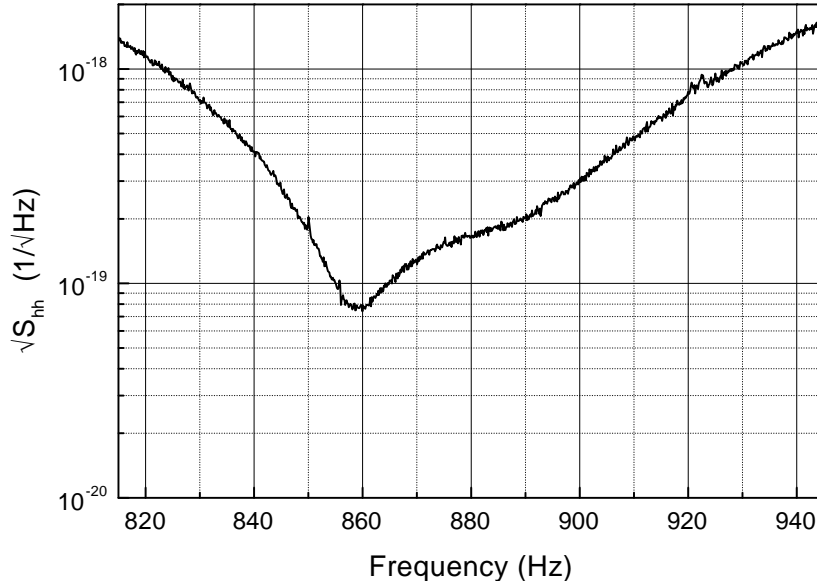


Figure 3. Strain sensitivity $\sqrt{S_{hh}}$ of the GW bar detector equipped with the optical readout. The sensitivity is mainly peaked in the neighbours of the mode (–) which has the higher Q value. The total bandwidth is ~ 25 Hz.

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 analyzed 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 trasducer. A continuous background with a well defined $1/f$ behavior 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 present, specially at lower frequencies. The Q factors for the two resonances of interest have been determined by decay time measurements, and they result to be $Q_- = 16600$ and $Q_+ = 8700$.

The locking procedure is manual and it takes typically less than 10 minutes. The system remained locked and operating for periods of about 24 hours on the average, and with a maximum time of 43 hours. 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 thermal stabilized and its temperature drift leads to a drift of the

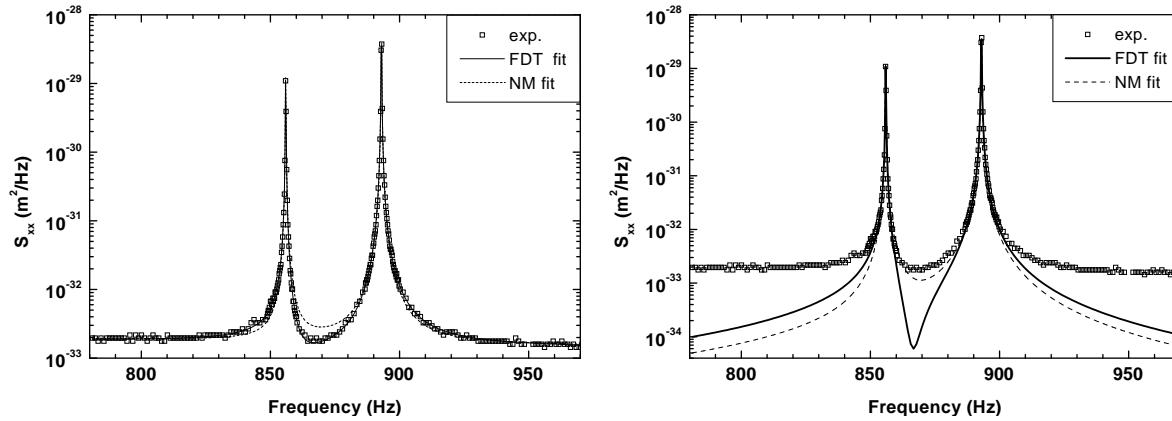


Figure 4. Left, fit of the experimental power spectral density. FDT: Fluctuation-Dissipation theorem. NM: normal mode expansion. Right, the fitted curves are plotted without the wideband $1/f$ contribution.

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 for mode hoppings which limits the continuity of the tuning to ~ 7 GHz, and when the laser approach a mode hop the locking fails. These mode hops can be approached also 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 Fig. 3 a typical strain amplitude noise. The contribution of the mode $(-)$ is more significative 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, can be estimated as $h_{\min} = 9 \times 10^{-17}$.

4. Thermal noise

The bar and the resonant trasducer can be schematized as a system of two coupled harmonic oscillators, at least in the neighbour 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 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 trasducer respectively. The different values we measured for Q_- and Q_+ , which can be explained in terms of different value of the original Q_b and Q_t , suggest that in our case the normal modes treatment can not describe the observed thermal noise.

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

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 the room temperature $T=296$ K. The fitted parameters are resumed in Table 1. The fit is not very sensitive to variations of the value of Q_b and this parameter is affected by a relative error larger 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 the fits are plotted in Fig. 4, together with the experimental data. The normal mode expansion clearly fails to fit the experimental data, specially in between the two resonances.

5. Conclusions and perspectives

We presented 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 $h_{\min} = 9 \times 10^{-17}$ 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. To this purpose cryogenic behaviour of the optical elements are currently under investigation.

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