Electro-optical Signal Readout for Gravitational Waves Resonant Detectors

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Abstract. We describe the design and the experimental implementation of an electro-optical transduction chain conceived for the gravitational waves (GW) bar detector AURIGA. Such a transducer is qualitatively different from devices presently operating and can represent an important step towards the realization of sensitive detectors included in GW observatories.

INTRODUCTION

Gravitational Waves (GW) were predicted by Einstein in 1916 in the framework of his theory of gravity. Since then the general relativity has been confirmed by several beautiful experiments, but a direct evidence of GW is still lacking. Due to the very weak effects predicted, the only feasible experiments are based on possible detection of signals from astrophysical sources. The strong world-wide effort dealt with is justified by the relevance of such an event and by the extraordinary impact on astrophysics and cosmology of a future GW observatory.

The search for GW signals is currently based on two kinds of detectors: the large interferometers [1] and the resonant detectors. They have different and somehow complementary characteristics and the most promising strategy is to take advantage of a network of sensitive detectors, also for the rejection of spurious signal which is particularly important in the case of a rare and intrinsically non-reproducible event. Cryogenic and ultra-cryogenic bars have reached a very high peak spectral sensitivity for frequencies around 1 kHz, thanks to the extremely low level of thermal noise. The best results are obtained by AURIGA [2] and NAUTILUS [3]: a peak sensitivity of $4{\cdot}10^{-22}$ $\mathrm{Hz}^{-1/2}$ in a bandwidth of about 1 Hz, giving a minimum detectable burst amplitude (S/N = 1) of $h^{\min} = 4{\cdot}10^{-19}$ [4,5]. Five resonant detector groups are now exchanging data in the framework of the International Gravitational Event Collaboration (IGEC) [6].

The AURIGA detector is based on a 3 m long, 2230 kg cylinder of aluminum alloy. This bar is kept under vacuum, suspended by a multiple mechanical isolator and cooled down to about 0.1 K where the mechanical quality factor is about $3 \cdot 10^6$ (first longitudinal mode). The sensitivity of resonant detectors is presently limited above all by the noise in the transduction chain which is used to transform the mass vibration into a readable signal. More precisely, the limitation comes from the noise of the SQUID amplifier following a capacitive transducer coupled to the bar. The improvement of this electronics is one of the tasks of the group, which has recently obtained very satisfactory and promising results [7].

An alternative solution is to use an optical transduction chain. This possibility has been explored in the past by Richard and co-workers, who proposed [8] and partially implemented [9] an optical signal extraction scheme. The progress in laser technology and optics allows us to design an advanced opto-electronic system which will consent an improvement of about one order of magnitude in burst sensitivity and an enlargement of the useful bandwidth from the present ~1 Hz to about 50 Hz. Apart from the increased sensitivity, the larger bandwidth allows for a more accurate timing and, as a consequence, coincidence analysis between detectors. Moreover, the use of two completely different transduction chains gives a better rejection of spurious signals originating from the transductor itself and permits to take advantage of the progress of the technology in different fields.

In this contribution we will discuss some details of our optical transduction chain and present some intermediate steps and preliminary results already obtained.

PRINCIPLE OF OPERATION

The main idea of an optical transduction chain is to exploit high Finesse Fabry-Perot cavities. The transmitted and the reflected fields of such cavities exhibit a comb of very narrow peaks when sweeping the optical frequency of a laser field entering in the cavity. These resonance frequencies corresponds to integer multiples of the Free Spectra Range (FSR = $c/2L$ where c is the speed of the light and L is the cavity optical length) and are proportional to the cavity length. The cavity Finesse is defined as the ratio between the width of the resonance peaks and the FSR and depends on the mirrors reflectivity. The peak signals allow to see the difference between the laser frequency and a cavity resonance frequency: if the former is fixed one can control the cavity length, while if the cavity length is stable one can see the laser frequency fluctuations.

The scheme of our transduction chain is based on the use of two Fabry-Perot cavities, which we call transducer and reference cavity [10]. The former is made by means of a mirror attached to the bar end face and a second mirror attached to a resonant mechanical transducer. The relative motion of the two mirrors is then converted into a frequency shift of the cavity optical resonance frequency. A Nd:YAG laser is frequency locked to the transducer cavity by means of a the FM sidebands

Pound-Drever technique [11] and its frequency fluctuations are monitored using the same technique with the stable reference cavity.

The system composed by the bar and the resonant mechanical can be viewed as two coupled harmonic oscillators. If their oscillation frequencies are the same, the bar vibration amplitude is amplified by a factor equal to the square root of the oscillators mass ratio and the detection bandwidth widens. The transducer is formed by a ~10 kg load on a thin elastic plate, both obtained from a single piece of high-Q Al alloy.

The transduction chain noise sources are given by the laser amplitude noise in two spectral regions: around the frequency used for the photodetection (in our case, 13.3 MHz) and around 1 kHz. The former effect limits the sensitivity of the detection, giving a wide-band noise in the signal at the end of the chain. On the other hand, the intensity fluctuations around 1 kHz are transformed into displacement noise by the radiation pressure effect on the cavity mirror, giving a back-action noise. These fluctuations are amplified roughly like the signal, i.e., according to the mechanical system transfer function, and is seen at the output as a narrow-band noise.

Both effects have a typical lower limit given by the laser shot-noise (which can, in principle, be overcome by quantum-non-demolition measurements). This limit can be reached if one pay attention to avoid 'technical' excess noise. An optimal (standard quantum limited) transduction chain is obtained when the two considered effects equally contribute to the total noise and, at the same time, the back-action overcomes the thermal noise. However, such performance is not straightforward with present technology. The cavity Finesse is limited to about 10^6 (we have planned a value of $3 \cdot 10^5$) and the laser power necessary to reach the standard quantum limit is several Watts, a value difficult to be managed both by cryogenic operation and by the mirror coatings. However, even with the parameters foreseen for our apparatus (reported in Table 1), the optical transduction chain seems very promising.

APPARATUS

The complete apparatus we are implementing includes:

- laser system
- reference cavities
- cryogenic optics and transducer cavity.

The parameters of the two optical cavities and the corresponding expected sensitivities for shot-noise limited detection are given in Tab.1.

TABLE 1.

Cavity	Finesse	Length (cm)	Laser power (mW)	Losses (ppm)	Freq. noise (Hz/√Hz)	Displacement noise (m/√Hz)
Transducer	300000	0.6	2	4	$2 \cdot 10^{-4}$	$4 \cdot 10^{-21}$
Reference	40000	20	5	4	$3.2 \cdot 10^{-5}$	$1 \cdot 10^{-21}$

The laser system is described in [12]. It is based on a commercial Nd:YAG source, with an output power of 100 mW. A critical point is the coupling of the laser radiation to a single-mode, polarization-maintaining optical fiber in order to reach the cryogenic room.

The laser intensity noise must be actively reduced in the spectral region around 1 kHz in order to avoid excess back-action noise. At this purpose, we have implemented a noise-eater by which the laser noise is reduced from 23 dB above shot-noise level (SNL) down to 5 dB, in agreement with the theoretical calculations for quantum-limited performance. The transmission through the optical fiber deteriorates this performance. From our measurements we deduce an amplitude noise 2 dB higher than SNL for the 2 mW power which we plan to couple to the transducer cavity. This corresponds to a back-action noise at least 5 dB lower than the transducer thermal noise, i.e., to a still negligible effect.

The FM sidebands technique allows to obtain the dispersion signal of a cavity resonance by mixing the resonant carrier (de-phased by the cavity) with the out-of-resonance sidebands (directly reflected by the input mirror). This technique has two good characteristics: the linear response nearby the resonance frequency and the enhancement of the detection frequency (corresponding to the FM modulation). The phase modulation must be performed in a frequency region where the laser amplitude noise is nearly at SNL and, at the same time, the detection can still be performed with high efficiency, low electronic noise, and high enough saturation level. The optimum region is 10÷15 MHz.

We phase modulate the laser with the optimum modulation depth (about 1 rad) using a resonant electro-optic modulator. Even if the phase modulation also produces an amplitude modulation, we have checked that we do not introduce any additional noise, around 1 kHz, in the signal recorded and de-modulated. This is true also after the propagation through the fiber.

The long term stability of noise eater and phase modulator is assured by an active thermal stabilization of the apparatus.

Reference Cavity And Laser Frequency Stabilization

The Fabry-Perot cavity is placed on a two-stages cantilever suspension, which provides vibrational insulation, and enclosed in a vacuum chamber, where a residual pressure of 10^{-6} mbar is maintained by means of an ionic pump. The whole chamber is thermally isolated. The temperature of the cavity can be varied from room temperature up to 100 °C, by heating the vacuum chamber, and kept constant within 1 mK through a PID stabilization loop driven by a PC and a multifunction digital board. Figure 1 shows the monitoring of the cavity temperature for several hours of operation.

The frequency of the laser is locked to a resonance peak of the cavity by means of the error signal provided by the FM sidebands technique. The frequency stabilization loop acts separately on the slow and fast controls of the laser, with unity gain frequency 0.1 Hz and 30 kHz respectively and a gain of 130 dB at 1 kHz. The frequency stability has been measured with a second identical cavity and monitoring its Pound-Drever signal, when the two cavities have equal resonance frequencies. This condition is achieved by changing the temperature of the cavities. Small changes of the cavity length is obtained by means of a system of piezoelectric actuators and invar

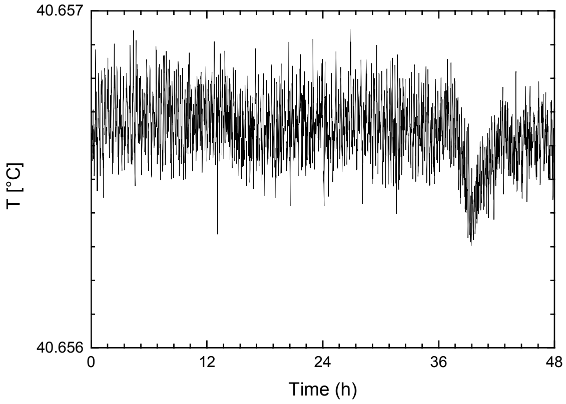

FIGURE 1 The temperature of the reference cavity is actively stabilized within 1 mK. The displayed temperature is measured with an independent probe

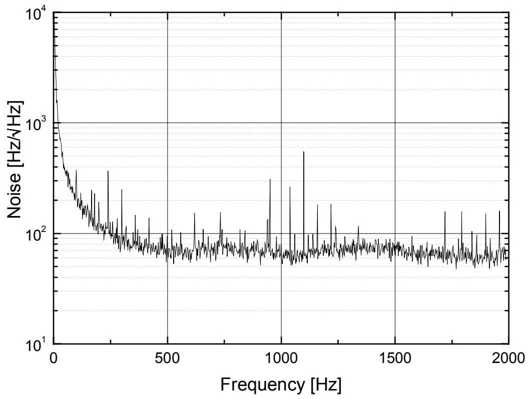

FIGURE 2 Frequency noise of the free-running laser

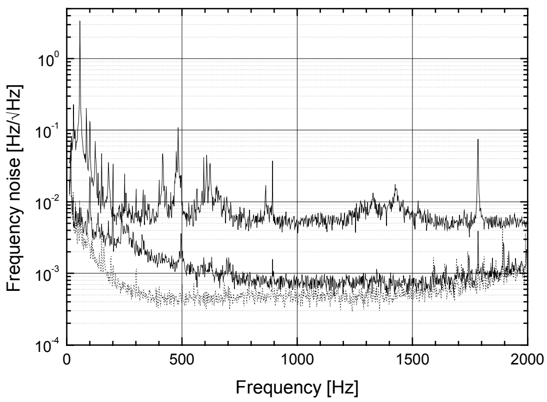

FIGURE 3 Frequency noise for the laser locked to the reference cavity (upper curve); amplitude noise (middle curve); electronic noise (lower curve).

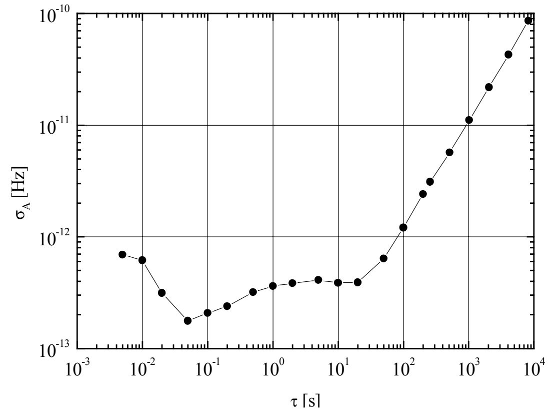

FIGURE 4 Allan deviation.

rods, which compress the Zerodur spacer of the cavity. Figures 2 and 3 show the frequency noise spectrum of the free-running laser (Fig.2) and of the locked laser, along with the post-demodulation amplitude noise measured out of resonance and the noise level of the photo detector electronics.

The frequency stability for longer time scales is measured by the Allan deviation σ_A plotted in Figure 4. The increase of σ_A for τ>10 s is essentially due to the natural drift which affect the cavities, even though thermally stabilized, corresponding to ~3 Hz/s. In the region between 10^{-2} and 10^{1}, the main contribution to σ_A comes from mechanical vibrations transmitted to the optical mounts from the table and transformed into frequency noise by Doppler and Sagnac effects.

Some tests have been done concerning cavity frequency noise induced by residual pressure in the vacuum chamber or induced by local heating of mirrors due to absorbed photons (photothermal effect).

Thermodynamic fluctuations of the density of the residual gas between the cavity mirrors result in fluctuations of the refraction index and as a consequence in additional

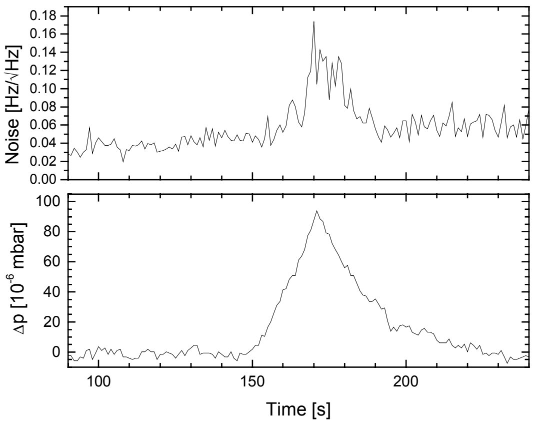

FIGURE 5 Effect of pressure on the frequency noise. Below, the pressure variation with the pump off. Above, the corresponding increase of the frequency noise level at 1 kHz.

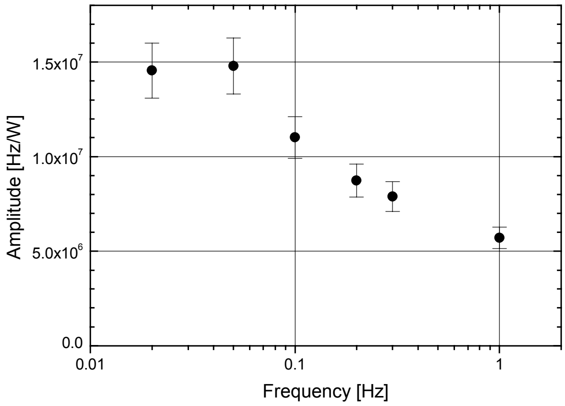

FIGURE 6 Frequency displacement per unit of dissipated power, as a function of the frequency of amplitude modulation.

frequency noise of cavity. Figure 5 shows how frequency noise increases with pressure when the ionic pump is temporary turned off. The increase well agrees with the predictions of a statistical model.

The light absorbed by mirrors produces a local heating, deforming the mirrors surface because of thermal expansion and finally changing the relative distance of the mirrors. When laser amplitude noise is considered, photothermal effect converts amplitude fluctuations into frequency fluctuations, giving a further contribution to the cavity frequency noise. To estimate this contribution we locked the laser to the reference cavity and slowly modulated the laser by acting on the noise-eater; then we phase-detected the corresponding changes in the resonance frequency of the monitoring cavity. Figure 6 shows the frequency displacement (reported to 1 W of absorbed laser power) as a function of the amplitude-modulation frequency. We also measured the phase delay between frequency displacement and amplitude modulation, finding –45° delay at ~2Hz. According to these preliminary measurements, the contribution of photothermal effect to frequency noise can be estimated to be $\sim 10^{-7}$ Hz/√Hz at 1 kHz, for 1 mW of dissipated power. This value assumes that our cavity losses are completely due to absorption in the mirror coating and need further investigations to be confirmed.

Transducer And Cryogenic Optics

The laser beam is carried into the bar vacuum chamber by means of an optical fiber which arrives to a small optical bench situated on the bar baricentral section, above the suspension point. On the optical bench (Fig. 7a) are situated an optical circulator, the mode-matching optics, two mirrors on optical mounts (tilters). In the present configuration also the photodetector is on the optical bench, but the laser radiation reflected by the cavity can be collected by a second fiber and detected outside the bar chamber. Two further mirrors bring the laser beam on the transducer cavity. The

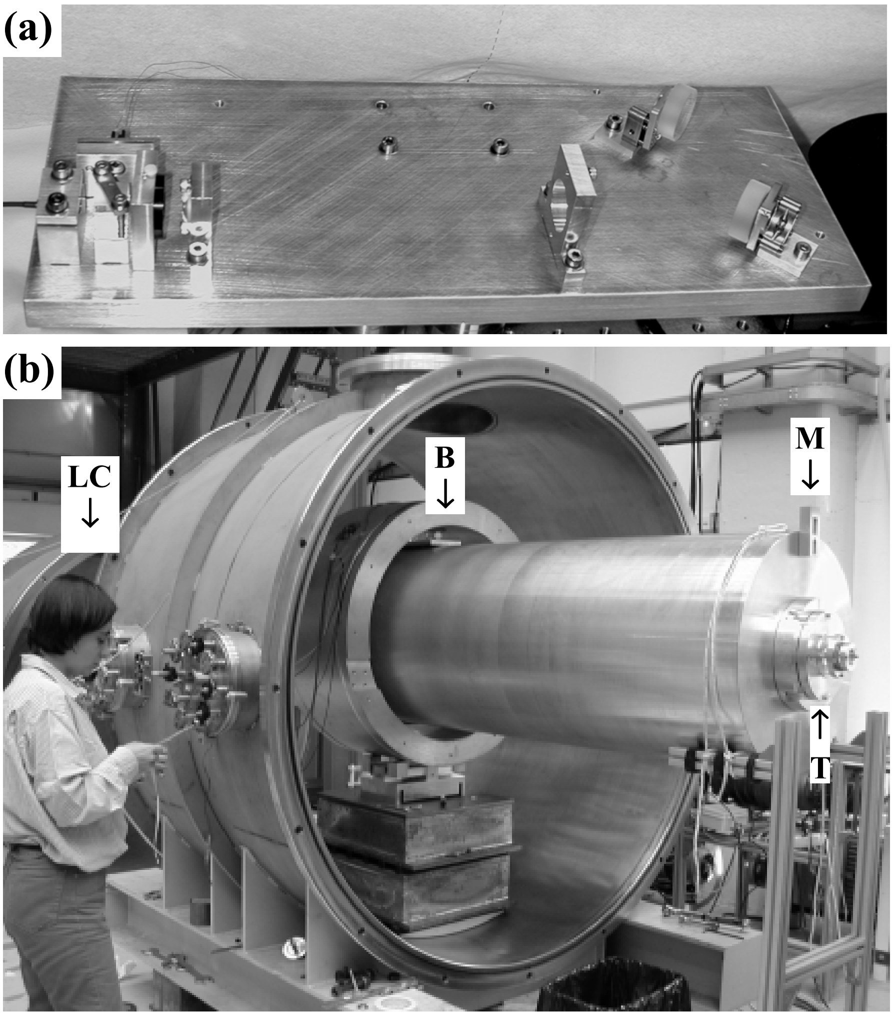

FIGURE 7 (a) Close view of the optical bench. (b) Room temperature bar. LC: Livia Conti; B: optical bench; M: mirror; T: trasducer cavity.

system is presently installed on a room temperature bar (Fig. 7b) equal to the cryogenic AURIGA detector, except for the simpler suspension system. Preliminary measurements with a simplified readout are reported in [13] and we are presently testing the complete system at room temperature conditions.

CONCLUSIONS

The research on GW will probably be one of the main tasks for future physics. The realization of GW detectors presently involves the state-of-the-art technology in several fields, such as mechanics, cryogenics, electronics, optics, opto-electronics, and even frontier physics research on quantum optics is expected to give its contribution in the near future. In this paper we have presented an example of this research effort, namely, the development of an optical transduction chain for resonant detectors. We have described some of the technical problems and details that must be considered and reported the present state of the experiment. The complete implementation of the optical transducer will allow a huge improvement in the performance of resonant detectors. Moreover, the use of different kinds of sensitive transducer based on completely different technologies will widen the possibilities of further developments and improvements, which are necessary for the realization of an efficient GW observatory.

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