An optical transduction chain for the AURIGA detector

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Abstract. We describe the principle of operation of an opto-mechanical readout for resonant mass gravitational wave detectors; with such a device the AURIGA detector is expected to reach a sensitivity at the level of $\sqrt{S_{hh}} = 10^{-22}/\sqrt{Hz}$ over a bandwidth of about $40Hz$. Recent developments in the implementation of this transduction chain are also reported. In particular we acheive quantum limited laser power noise in the frequency range of $200Hz$ around the bar fundamental frequency (about $1kHz$) by means of active stabilization. We also set up a reference cavity of finesse 40000 with optically contacted mirrors on a $0.2m$ long Zerodur spacer. The cavity can be heated from room temperature to about $100°C$ and temperature stabilized with fluctuations within $1mK$ over a period of several days. The cavity is under vacuum and isolated from mechanical disturbancies by means of a double stage cantilever system.

INTRODUCTION

The sensitivity of presently working g.w. detectors, which are of the resonant type, is limited by read-out noise [1]. As a result, in the past several kinds of devices have beeen proposed to detect the small vibration of a resonant bar determined by the passage of a gravitational wave. One of the most appealing one is that proposed by J.P.Richard [2], who suggested to use laser interferometric techniques for this purpose. Actually Richard not only suggested the new idea and calculated the expected sensitivity, but also begun the needed experimental work [3].

A more recent version of the Richard's idea is the object of the work described in this paper. The transduction chain is designed in order to take fully advantage from the fast growing technical improvements in the optics industry and takes into account the many problems that an integration into a real detector may arise.

PRINCIPLE OF OPERATION

The fundamental idea for signal optical transduction is to have a resonant optical cavity of lenght L formed by a mirror attached to a bar end face and a second fixed mirror. Then a relative motion ΔL of the two mirrors, due to bar vibration induced eventually by a g.w., is converted into a change $\Delta\nu$ of the optical resonant frequency ν according to:

$$\frac{\Delta L}{L} = \frac{\Delta\nu}{\nu} \tag{1}$$

If the second mirror is not fixed but is attached to a resonator having the same frequency as the bar (i.e. to a resonant transducer) then the bar vibration amplitude can be amplified by a factor equal to the square root of the oscillators mass ratio. The system formed by a bar and a resonant transducer can be viewed, indeed, as that of two harmonic oscillators coupled together.

The idea expressed in eq.(1) has been developed in the scheme shown in Figure 1 [4]. The optical resonant cavity cited above is here named *transducer cavity*. The phase modulated beam produced by a Nd:YAG laser source is split in two

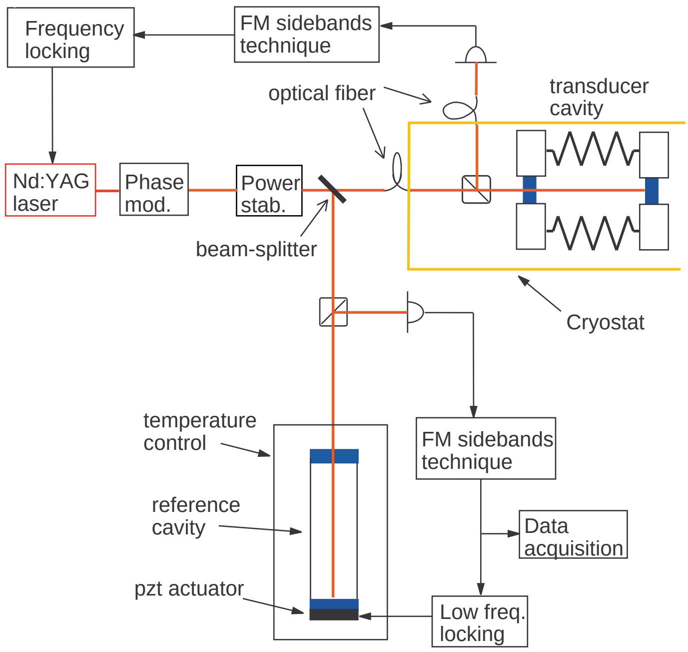

FIGURE 1. Scheme of the optomechanical readout for resonant bar g.w. detectors.

parts, one of which is sent to the transducer cavity inside the cryostat that houses the bar by means of an optical fiber. The reflected beam is conveyed into another fiber cable and is then detected by a photodiode outside the cryostat. The error signal obtained with the Pound-Drever-Hall technique [5] is used by a servo system to frequency-lock the laser source to the transducer cavity; thus the light frequency carries information on the bar motion.

In order to extract this piece of information, the second beam is sent to a second Fabry-Perot cavity, called *sensing cavity*, which acts as frequency reference. Again, the reflected beam is detected by a photodiode and its current used to obtain a signal which is proportional to the frequency difference between the sensing cavity and the laser. In this way, this error signal carries information on the bar and transducer motion and is to be analysed for g.w. detection. Anyway, at this purpose, one must guarantee that the sensing cavity is in resonance condition with the light: therefore one has to correct its length at low frequency (i.e. in a frequency range far from the kHz range, e.g. up to some tens of Hz) in order to follow any slow drift of the transducer cavity (due for instance to temperature variations). The error signal to be used for such controls is the same that, at higher frequencies, is acquired for g.w. detection.

An important point that should be made is that laser power noise acts as a *back-action noise*, in the sense that it ends up exciting and heating the system of bar and transducer. This occurs because the laser intensity noise induces fluctuations in the radiation pressure on transducer cavity mirrors, thus generating a noise force. For this reason it is important that the laser power noise is reduced before entering the cryostat.

With the figures given in Table 1, the expected total strain noise referred at detector input reaches minimum level of $\sqrt{S_{hh}} = 10^{-22}/\sqrt{Hz}$ and the useful bandwidth (defined at $+3dB$ for S_{hh}) is about $40Hz$ in a frequency range centered on detector resonance. Assuming that the signal is a $1ms$ burst of g.w. with central frequency equal to bar resonance, the wave amplitude that can be detected with unitary signal-to-noise ratio is: $h_{min} = 3 \cdot 10^{-20}$.

TABLE 1. Parameters used for calculating the sensitivity of a bar detector equipped with the optical readout.

bar temperature	$0.1K$	transducer effective mass	$6.5kg$
bar res. freq.	$920Hz$	Q_{bar}	$5 \cdot 10^6$
transd. res. freq.	$920Hz$	Q_{transd}	$5 \cdot 10^6$
trasd.-cav. length	$0.01m$	sens.-cav. length	$0.2m$
laser wavelength	$1064nm$	mirror losses	$1ppm$
sens.-cav. input mirror T	$150ppm$	sens.-cav. output mirror T	$2ppm$
transd.-cav. input mirror T	$15ppm$	transd.-cav. output mirror T	$2ppm$
photodiodes quantum efficiency	0.85	laser phase mod. amplitude	$0.96rad$
transd.-cav. input power	$2mW$	sens.-cav. input power	$5mW$

LASER POWER NOISE

The first task was to reduce the laser intensity noise in the $1kHz$ region of the laser source: the experimental setup is shown in Figure 2 and follows ref. [6]. The linearly polarized laser beam enters an electro-optic modulator (EOM) with the crystal axis sligtly rotated with respect to the laser polarization direction; the EOM is followed by a polarizer parallel to the input light polarization. The output beam passes through a beam-splitter with reflectivity R: the reflected beam is detected by a photodiode whose output, properly amplified, is fed back to the EOM. The outgoing beam is that to be used in the experiment: for measureament purpuse, this beam was split by a 50% beam-splitter and the beams detected by two balanced photodiodes, whose outputs were summed and/or subtracted. The subtraction gives the shot noise level of the beam impinging the beam-splitter.

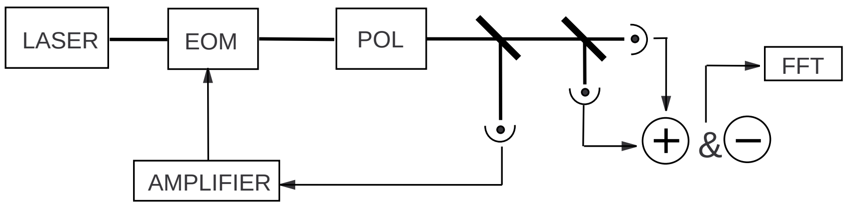

FIGURE 2. Experimental setup for the laser intensity noise reduction and measurement.

The free-running laser intensity noise was thus measured and compared to shot noise level: the calibration was checked using a halogen lamp, whose intensity power noise around $1kHz$ was found to scale linearly with intensity, as expected from shot noise limited light fluctuations. The measureaments in the frequency range $(900 \div 1100)Hz$ are shown in Figure 3 (left): the reflectivity R of the first beam-splitter was varied by replacing it with a half-wave plate followed by a polarizing beam-splitter. The measureaments were repeated with the intensity noise reduction loop switched on and are shown in Figure 3 (right): experimental points are fitted by a theoretical curve with constant total loop gain (dashed line). Best achievable performance can be obtained with infinite total loop gain [7], as shown in Figure 3 (right; solid line).

The intensity noise was also measured at the output of a single-mode polarization maintaining optical fiber, coupled to the outgoing beam: the fiber was found to deteriorate the acheived laser intensity noise reduction, maximally at low frequencies as evident from Figure 4. This figure refers to beam-spitter $R = 50\%$ and $15mW$ transmitted by the fiber: the measured noise power is $8dB$ above the shot level, in the frequency range of interest. Scaling this to the $2mW$ fed to the transducer-cavity, the acheived intensity stabilization will allow the power reaching the resonators to be close to the shot-noise limit.

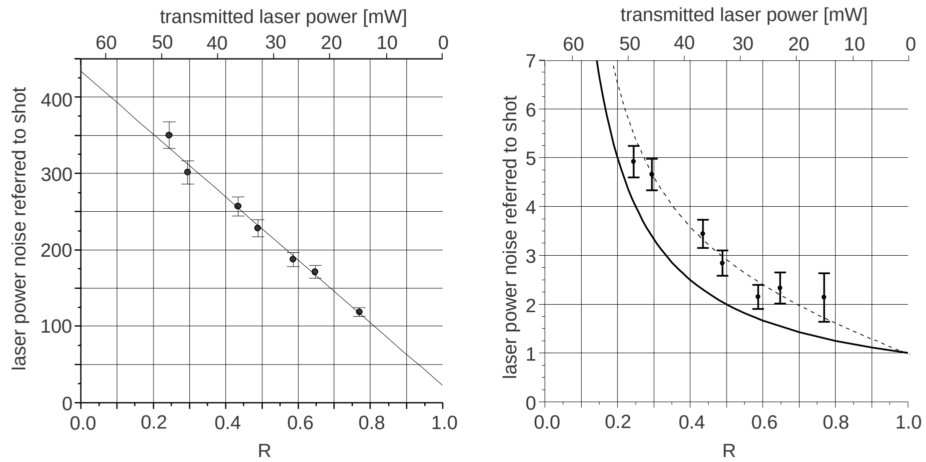

FIGURE 3. Laser intensity noise power spectrum integrated between 900 and $1100 Hz$ referred to the shot noise level with intensity noise reduction loop off (left) and on (right). Left: experimental points and fitting curve. Right: experimental points, finite loop gain fit curve (dashed line) and infinite loop gain limit (solid line).

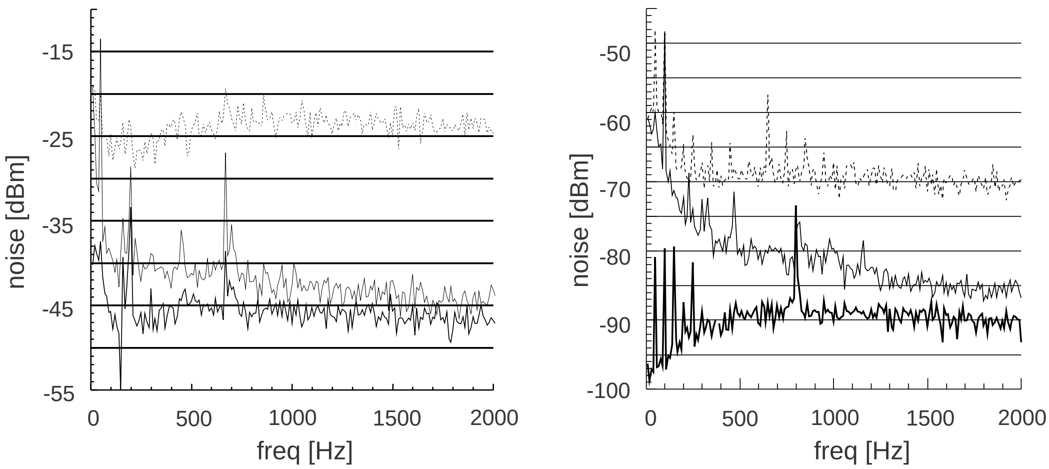

FIGURE 4. Performance of the laser intensity noise reduction; spectra refer to the out-of-loop beam (after an amplification stage). Left: free running laser (upper curve), corresponding shot-noise level (lower curve) and stabilized laser beam (middle curve). Right: free running laser transmitted by a singlemode optical fiber (upper curve), corresponding shot-noise level (lower curve) and fiber transmitted stabilized laser beam (middle curve).

REFERENCE CAVITY

As said above, the signal detection is performed at the sensing-cavity that acts as frequency reference. Therefore its own frequency stability should be better than that of the laser with respect to the transducer-cavity. With the values in Table 1 the shot noise limits the laser frequency locking to the transducer-cavity to $1 \cdot 10^{-4} Hz/\sqrt{Hz}$ (bilateral). A laser beam sent to a sensing-cavity with the characteristics described in Table 1 can be locked with a shot-noise limited frequency noise at the level of $3 \cdot 10^{-5} Hz/\sqrt{Hz}$. Obviously all the other noise sources must be negligible with respect to this level. The main sources come from thermal noise, lenght fluctuations induced by temperature ones, mechanical disturbancies and residual gas pressure variations. Presently we are planning to use a room temperature sensing cavity, which can be temperature tuned to resonance. Once the correct lenght is thus reached, the temperature is stabilized and the cavity is kept resonant by means of piezoelectric actuators (PZT) acting below the bar resonant frequency. The cavity is made out of a Zerodur spacer with optically contacted mirrors (measured finesse $4 \cdot 10^4$). Slow laser frequency variations are followed by changing the temperature. In order to prevent the electric and thermal noise of the actuators from compromising the frequency stability of the cavity, the actuators are mounted so that the effect of piezo motion is reduced down to the minimum necessary level. For a typical piezoelectric ceramic, a reduction by a factor 100 is accomplished by mounting the cavity as in Figure 5.

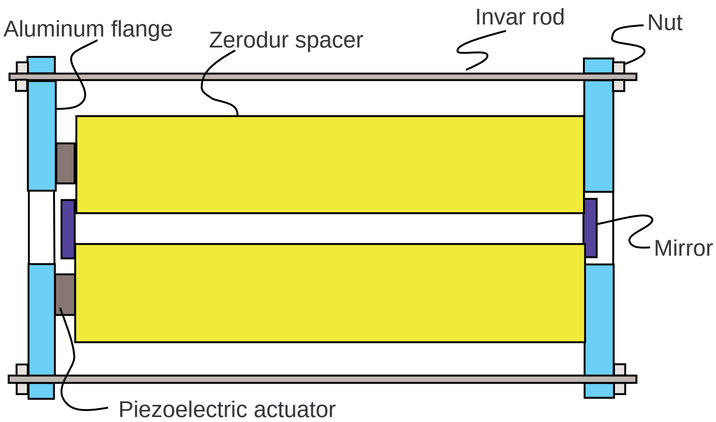

FIGURE 5. Schematic cross-section (not drawn to scale) of the sensing-cavity assembly.

The cavity is placed on the top of a double stage cantiveler suspension and is kept under vacuum by pumping with a ionic pump, which has the advantage of being vibration free. Following the calculations of ref. [8], the vacuum level for N_2 should be as good as $6 \cdot 10^{-7} mbar$. The cavity temperature can be changed from room temperature up to about $100°C$, enough for covering a free spectral range (the thermal expansion coefficient of Zerodur is $\sim 4 \cdot 10^{-8} K^{-1}$ [9]). The temperature is then actively stabilized and temperature variations are measured to be less than $1mK$ for periods of several days: this is enough to stay within a cavity optical width just with the temperature control.

At present two reference cavities have beeen built in Florence in order to measure the frequency stability of one with respect to the other. The laser has been frequency locked to one of the two cavities with the necessary stability and work is in progress for completing the measurements.

THE TRANSDUCER

Experimental work on the mechanical resonator contituing the transducer has been described elsewhere [4,10]. A $50mW$ Nd:YAG laser beam was fed by means of a single-mode fiber to a $\sim$ 1200 finesse Fabry-Perot cavity installed on a room temperature bar identical to the one used in AURIGA. The laser was frequency locked to this cavity for short time periods and the resonant modes of the bar and transducer assembly excited by thermal noise were observed in the correction signal. Present work is devoted to improving the mechanical Q of the assembly and the laser frequency locking to the cavity. Once this is reached and the signal compared to a reference cavity, a complete optical read-out for a bar detector, even if at room temperature, will be first realized and its sensitivity and reliability studied. A further effort is needed if the device is to be used in a cryogenic detector: optics and fiber behaviour at low temperature is to be investigated and a cryogenic system to guarantee the transducer-cavity alignment even during the cooling down has to be implemented.

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