Developments and Cryogenic Measurements of an Optical Transducer for the Gravitational Wave Detector AURIGA

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The Crab Nebula in Taurus, distance 6300 light-years, diameter 10 light-years, expansion velocity 1800 km/s. Remains of the supernova observed on the 4th of July 1054 A.D. in China and America; it remained visible to the naked eye in daylight for 23 days and in the night sky for 653 days. In the center (not visible), a Pulsar with a pulse frequency of 30 Hz, presumably emitting gravitational radiation.

Photograph by European Southern Observatory, 17 November 1999.
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Chapter 1

Introduction

For thousands of years people have been studying the universe. The universe was observed through the part of the electromagnetic spectrum our eyes are sensitive to, visible light. The observations were done using the naked eye, until in the early 17th century the first instrument, the telescope, was introduced by Galileo Galilei (1564-1642). As this instrument improved over the centuries, we learnt more about the universe, although still using only light.

In the 1930’s radio waves were discovered, and this created a revolution in our view of the universe. Because of a difference in wavelength of a factor $10^7$, an entirely different range of phenomena was observed; the universe no longer seemed serene and steady, dominated by stars and planets evolving on a timescale of millions or billions of years. Instead the universe appeared violent, with events on a time scale of days, hours or seconds. Nonetheless, like visible light, radio waves are still electromagnetic waves.

Gravitational waves are a type of radiation that is fundamentally different from electromagnetic radiation. Their discovery could open an entirely new window to the universe and, like radio waves in the 1930s, set off a revolution in astronomy. The study of black holes for example, which don’t emit electromagnetic radiation but do produce gravitational waves, would benefit greatly of such a discovery. Gravitational waves in fact provide the only way to make direct observations of these objects. Moreover, gravitational waves are produced by the asymmetrical acceleration of mass, so the information they contain comes mainly from the internal parts of massive objects or violent events that emit them. This is an advantage with respect to the electromagnetic waves that reach us, which are produced by the superficial clouds of objects and therefore give us less, and indirect information.

Because gravitational waves interact weakly with the medium they trespass, they tend to propagate through space almost unperturbed. This is a reason for them to be very interesting because of the large distances the radiation can travel without losing much information, but it also makes them very difficult to detect. Because of this weak interaction, gravitational wave detectors have to be extremely sensitive. The
search for gravitational waves already started more than 40 years ago, but no gravitational waves have ever been detected by any instrument.

Joseph Weber was the first to start working on detecting gravitational waves in the early 1960s. He built the first gravitational wave antenna, at the University of Maryland (USA), which consisted of a large solid aluminum cylinder of about 1500 kg suspended in a vacuum chamber, operating at room temperature and using a series of piezo electric crystals to monitor the oscillations of the bar. Because he realized that coincidence measurements between at least two detectors would be necessary, he constructed a second detector near Chicago, at a distance of about 1000 km from the first antenna. After he reported the simultaneous excitation of the two detectors, many groups built similar detectors to verify his results. Although they managed to improve the sensitivity significantly, no coincidences were measured. It turned out that the events that Weber had detected were not due to gravitational waves.

Forty years later the search for gravitational waves still continues. Two types of ground-based gravitational wave detectors exist today: interferometric detectors and resonant mass detectors. The interferometric detectors are based on the Michelson Interferometer, and have arm lengths varying from 20 meters up to 4 kilometers. Interferometric detectors presently in operation or under construction are LIGO (USA), VIRGO (France/Italy), GEO600 (Germany/UK), TAMA300 (Japan) and AIGO (Australia).

Also a space-based interferometric detector called LISA (Laser Interferometer Space Antenna) is presently being developed. This antenna, with an arm length of 5 million kilometers, consists of three spacecrafts in orbit around the sun. LISA is a joint project of NASA and ESA, and will be launched in 2013.

Resonant mass detectors aim at signals of a different frequency than the interferometric detectors, and exist in two forms: cylindrical bar antennas and spherical antennas. The bar antennas are basically of the type that Joseph Weber constructed in the 1960s, although improved significantly in terms of operating temperature (nowadays the detectors operate at (ultra)cryogenic temperatures to reduce thermal noise), construction material, vibration isolation, transducers, amplifiers and data acquisition and analysis. A number of groups around the world are operating this type of antenna: ALLEGRO (Louisiana, USA), EXPLORER (CERN, Switzerland), NAUTILUS (Rome, ITALY), and AURIGA (Padova, Italy).

Another type of resonant detector is the spherical detector, which basically works the same way as a bar antenna. An advantage of spherical detectors is the fact that they are isotropic (i.e. equally sensitive in all directions), which makes it possible to determine the direction from which the gravitational wave is coming with just one detector. The first spherical detector that has been built is MinIGRAIL (Leiden, The Netherlands), two other spherical detectors are under construction: SFERA (Rome, Italy) and SCHENBERG (Sao Paolo, Brazil).

The main part of the experimental work for this thesis was done at the AURIGA laboratory, at the Laboratori Nazionali di Legnaro, Istituto Nazionale di Fisica Nucleare, Padova, Italy, from September 2003 until July 2004 and regarded the development and mechanical quality factor measurements of an optical transducer. A minor part of the experimental work for this thesis, namely the development and
mechanical quality factor measurements of the second stage of an inductive transducer, was done at the site of the spherical gravitational wave detector MiniGRAIL in the Kamerlingh Onnes Laboratory, Leiden University, The Netherlands, from April until July 2003.

The AURIGA ultra-cryogenic gravitational wave bar detector consists of an Al5056 cylinder (length 3 m, diameter 60 cm, mass 2.3 tons) suspended horizontally at the center of mass. Its first longitudinal mode is at about 920 Hz at cryogenic temperatures. When a gravitational wave hits the bar, the bar absorbs energy from the gravitational wave; the energy absorption is maximal when 1) the wave propagation direction is perpendicular to the longitudinal axis of the bar, and 2) the wave frequency matches the bar resonance. This absorbed energy induces a vibration, which is picked up by the transducer. The goal is to be able to detect a relative length change $h$ of the bar, which is defined as $\Delta L/L$, of the order of $10^{-20}$ (with $\Delta L$ the total length change of the bar).

For AURIGA, an opto-mechanical readout (optical transducer) is being developed [1]. As part of the optical transducer, a high mechanical quality factor ($Q$) oscillator is coupled and tuned to the bar, which mechanically amplifies the vibration. The mechanical signal due to the excitation of the bar by the passing gravitational wave is then converted into an electrical signal using an optical readout. The bar vibration is detected by means of a resonant optical cavity, called a Fabry-Perot cavity, formed between the bar and the transducer. The bar vibration induces a time varying relative displacement between bar and transducer, thus modulating the length of the cavity, i.e. its optical resonance frequency. The used laser source is, via a feedback loop, frequency-locked to the cavity, and thus its frequency changes with it. With a reference cavity, whose optical resonance frequency is kept fixed, this modulation in laser frequency, possibly carrying a gravitational wave signal with it, is monitored.

A full test of the bar with optical transducer has already been done at room temperature [1], and a test at low temperature is planned for the near future. At low temperature the thermal noise is lower because of the lower thermodynamic temperature and because the mechanical quality factor is expected to rise by 3 orders of magnitude relative to room temperature. The optical transducer could also be used for future projects as the dual detector, which is in the phase of research now at the AURIGA group. This detector would have a totally new configuration, consisting of either two concentric spheres or two coaxial cylinders; it could have a large bandwidth and might be the next generation of resonant gravitational wave detectors (see for example [2]).

This thesis contains besides this introduction the following chapters:

**Chapter 2: Gravitational Waves, Sources and Detectors:**
What are gravitational waves and what are their possible sources? Also the gravitational wave detectors existing today (or in development) will be summarized, concluding with a description of the main characteristics of the AURIGA detector.

**Chapter 3: The Optical Transducer:**
First a brief overview of the three most commonly used types of transducers is given, one of them being an inductive transducer (on which some measurements have also been done for this thesis) after which the optical transducer is described in more
detail. Finally the most important noise sources and the sensitivity of the optical transducer are discussed.

**Chapter 4: Mechanical Quality Factor of the Al5056 Resonator:**
This chapter begins with a description of the experimental setup of the measurements that have been performed to test the mechanical quality factor of the Al5056 resonator, which is the mechanical amplifier stage of the optical transducer. Then the four cryogenic measurement runs are described and the results given.

**Chapter 5: Conclusions:**
The measurements and results given in chapter 3 and 4 are discussed, on the basis of which some recommendations for the future are made.
Chapter 2

Gravitational Waves, Sources and Detectors

2.1 What are gravitational waves?

Gravitational waves are ripples in the curvature of spacetime that propagate with the speed of light. They are the spreading out of gravitational influence. When the gravitational field of an object changes, the changes ripple outwards through space and take a finite time to reach other objects. These ripples are called gravitational radiation or gravitational waves. Because gravity is non-linear, it is not possible in a fully precise manner to separate the contributions of gravitational waves to the curvature of spacetime from the contributions of the earth, the sun, the galaxy or anything else; this means that gravitational waves are not precisely defined entities [3]. Figure 2.1 illustrates the curvature of spacetime.

Figure 2.1: Illustration of the curvature of spacetime by massive objects like stars and planets (picture from [4]).
On the other hand, in realistic astrophysical situations the length scale on which the waves vary is very short compared to the length scales on which all other important curvatures vary. This makes possible an approximate split of the Riemann curvature tensor $R_{\alpha\beta\gamma\delta}^{\text{B}}$ into a ‘background curvature’ $R_{\alpha\beta\gamma\delta}^{\text{B}}$ plus a contribution $R_{\alpha\beta\gamma\delta}^{\text{GW}}$ due to the gravitational wave. This method of defining a gravitational wave is a special case of a standard technique in mathematical physics often called shortwave approximation, and is connected to the WKB approximation.

There is an elegant shortwave-approximation formalism for gravitational-wave theory due largely to Brill and Hartle (1964) and to Isaacson (1968). The formalism reveals that general relativistic gravitational waves propagate through vacuum in essentially the same manner as light, with the same speed, with the same changes of amplitude due to the curvature of wave fronts, with the same diffraction effects when focused by a gravitational lens, etc.

Gravitational waves have, like electromagnetic waves, only two independent components- two polarization states. They produce a quadrupolar, divergence-free force field. This force field has two components corresponding to the two polarization states of the waves: the quantity

$$h_+ \equiv h_{xx}^{TT} = -h_{yy}^{TT}$$

produces a force field with the orientation of a ‘+’ sign, while

$$h_\times \equiv h_{xy}^{TT} = h_{yx}^{TT}$$

produces one with the orientation of a ‘×’ sign (TT stands for Transverse-Traceless. The TT-gauge is the reference frame of a particle in free fall).

Thus $h_+$ and $h_\times$ are called the ‘plus’ and ‘cross’ (or + and ×) gravity-wave amplitudes. From these amplitudes and the polarization tensors $e_{xx}^+ = -e_{yy}^+ = 1$, $e_{xy}^- = -e_{yx}^- = 1$ (all other components zero), one can reconstruct the full wave field:

$$h_{jk}^{TT} = h_+ e_{jk}^+ + h_\times e_{jk}^\times$$

Figure 2.2 shows the force field of a gravitational wave with ‘+’ polarization and with ‘×’ polarization. The effect of a gravitational wave on a ring of test particles is shown in Figure 2.3.
Extensive literature exists on the theory of gravitational waves and their mathematical description, as derived from Einstein’s theory of General Relativity; see for example [3], [5].

### 2.2 Sources of gravitational waves

Gravitational waves are produced by the asymmetrical acceleration of mass. In the following a brief overview of the expected gravitational wave sources is given. But until direct observations of gravitational waves are successfully made, we are not entirely sure what sources will be seen. However, there are many sources that could be strong enough to be seen by the present day detectors.

To begin with, one source can be ruled out: man-made gravitational radiation. Calculations on what would be needed to create gravitational waves in a laboratory here on earth, strong enough to detect them, show that it is practically impossible to do so [6],[33]. Consider a bar made of steel with a length of 100 meters, spinning around an axis perpendicular to the bars longitudinal axis (see figure 2.4). The emitted energy will be maximal if the bar spins at its maximum frequency before it will break, at about 3 Hz (\( \omega = 20 \text{ rad s}^{-1} \)).

![Figure 2.4: Rotating bar to create gravitational waves [7].](image)
The total emitted power (luminosity) of gravitational radiation is about

\[ L_b = \frac{2}{45} \frac{G}{c^5} m_b^2 l_b^4 \omega^6 \sim 10^{-26} \frac{J}{s} \]  

(2.4)

where \( m_b \) and \( l_b \) are the mass and the length of the bar and \( \omega \) the angular frequency of the rotation. \( G \) is the gravitational constant, \( c \) the speed of light. The energy cross section for gravitational waves of one of the bar detectors operational these days is about \( 10^{-25} \, \text{m}^2 \, \text{Hz} \). This means that the total energy absorbed by the detector would be of the order of \( 10^{-47} \, \text{J/s} \). The energy of one graviton at that frequency is about \( 10^{-32} \, \text{J} \). Even if the detector were able to detect one graviton, the time between two detections would be about 6 million years. We therefore depend on astrophysical sources for detectable gravitational waves. In general there are three types of astrophysical sources [8]:

- **Burst sources**: typically last less than one second. They are produced by violent events like supernova explosions, merging of binary systems and Gamma Ray Bursts.

- **Periodic waves**: have an almost monochromatic spectrum and last very long. They are produced by rotating neutron stars or inspiraling binaries of compact stars or black holes.

- **Stochastic waves**: have the characteristics of noise, and are therefore described by a (flat) power spectrum and an autocorrelation function. The stochastic background of gravitational radiation is a superposition of all gravitational waves emitted in the past. It should have a principal cosmological component at low frequency, remaining from the era of inflation, a very early phase of the universe. Another possible source could be great heaps of neutron stars in the center of our galaxy creating, due to their mutual attraction, a complex signal that can also be thought of as stochastic.

Now we will discuss shortly some specific potential sources of gravitational waves which are interesting for the present day bar detectors like AURIGA (section 2.3) or spherical detectors like MiniGRAIL (section 2.2).

1. **Supernova explosions**

There are two types of supernovae, of which the second type is the most promising source of gravitational waves. This type of supernova occurs when a massive star \((M \geq 9 M_{\odot})\) runs out of combustion fuel, meaning that the outward pressure vanishes and the star implodes under influence of its own gravity, with violent emission of the outer layers. What results is a compact neutron star or a black hole that while oscillating generates gravitational waves. The amplitude of these waves depends mainly on the amount of mass that is converted into gravitational radiation due to the ellipticity (deviation from sphericity) of the event [6], and is given by:
where \( \varepsilon = \frac{\Delta E_{GW}}{M_{\text{sun}}c^2} \) is the fraction of energy emitted in gravitational waves in units of solar mass \( M_{\text{sun}} \), and \( \Delta E_{GW} \) the energy converted into gravitational radiation with frequency \( v \). Then \( r \) is the distance to the source and \( \tau \) the pulse duration. The expected rate of occurrence is about 60 events per year within a range of 10 Mpc.

2. **Coalescence of compact binaries**

A binary system consists of two bodies orbiting each other (figure 2.5). The most interesting systems in terms of gravitational wave sources are systems consisting of either two neutron stars, two black holes, or a neutron star and a black hole. Such a system looses energy (caused by the orbital motion) which is converted into gravitational radiation. The stars will gradually get closer together until they finally merge. There are actually three phases in this process (inspiral, coalescence and ring-down [6]), for which the gravitational waves have different properties. Fig. 2.5: Inspiraling binary [9]

During the phase of coalescence the amplitude of the emitted gravitational wave is:

\[
h = 1.7 \times 10^{-21} \left( \frac{\varepsilon}{10^{-21}} \right)^{\frac{1}{2}} \left( \frac{10 \text{Mpc}}{r} \right)^{\frac{1}{2}} \left( \frac{1 \text{kHz}}{v} \right)^{\frac{1}{2}} \left( \frac{10^{-3} \text{s}}{\tau} \right)^{\frac{1}{2}} (2.5)
\]

with \( d \) the distance between the two bodies, \( v \) the frequency with which the bodies are inspiraling, and \( m \) the masses of each of the two bodies which were assumed to be the equal. The expected rate is a few events per year, within a range of 60 Mpc.

3. **Rotating neutron stars**

Out of supernovae often originate fast rotating neutron stars, called pulsars (figure 2.6). If the period of rotation is 1 millisecond or smaller, instabilities occur that cause a breaking of the axial symmetry. As a consequence, periodic
gravitational waves are emitted with a frequency of twice the rotational frequency of the star. Most of the pulsars observed have a frequency of 10 to 100 Hz, but pulsars with a frequency of over 1kHz have also been observed. If we look at a pulsar with radius $R$ and a frequency $f$, the radiation amplitude will be:

$$h \propto \left( \frac{2\pi R f}{c} \right)^2 \frac{G m}{rc^2}$$

(2.7)

with the $m$ mass of the pulsar and $r$ the distance to the source.

![Figure 2.6: Drawing of a pulsar, which is a fast rotating neutron star. Gravitational waves can be emitted at a frequency of twice the star rotational frequency][9].

## 2.3 Gravitational wave detectors

Two types of gravitational wave detectors are in use today: laser interferometers and resonant detectors. In the next two subsections we will describe both types. In order to compare the sensitivity of the detectors, the strain spectral sensitivity $\sqrt{S_{\nu}}$ (dimension $Hz^{-1/2}$) is often used.

### 2.3.1 Interferometric detectors

In fact it was Joseph Weber, the man who built the first cylindrical bar detector in the 1960s, who also proposed the idea of building laser interferometers to detect gravitational waves. Laser interferometers are based on the Michelson interferometer. With such an interferometer one can accurately determine the change in distance between two mirrors of one arm by looking at the interference pattern with the beam of the other arm. This way the deformation of space by the gravitational wave can be detected. See for example [10].

A number of laser interferometers have been built or are under construction around the world. There is the American LIGO project, which has two large interferometers (armlength of 4 km) at different locations: one in Livingston (USA), the other in Hanford (USA), and a smaller interferometer (armlength 2 km) also in Hanford. A French/Italian interferometer called VIRGO (figure 2.7) with arms of 3 km is located near Pisa (Italy). In Hannover (Germany) a smaller detector called GEO600 with arms of 600 m is situated, which is a German/British collaboration, and still smaller is...
TAMA (Japan) which has 300m arms. A prototype interferometer called AIGO is under construction near Perth (Australia). Laser interferometers can in principle achieve very high sensitivity, of the order of $10^{-22}$ to $10^{-24}$ in strain spectral sensitivity $S_{\text{hh}}$, with a bandwidth of more than 1 kHz.

To be able to detect low frequency signals coming from massive black holes and binaries, a space based laser interferometer is under construction, the Laser Interferometer Space Antenna (LISA), which is a joint project of NASA and ESA. It will consist of three spacecrafts orbiting the sun in the same orbit as Earth, at a 20° angle behind Earth (see figure 2.8). The three spacecrafts will constitute a triangle with an arm length of 5 million kilometers, with laser beams between them, working as a Michelson interferometer. LISA will have a sensitivity similar to that of the ground based interferometers, between $10^{-4}$ to $10^{-1}$ Hz. A prototype, the LISA pathfinder, is scheduled for launch in 2007. LISA itself is planned to be operational in 2013.

### 2.3.2 Resonant detectors

A resonant-mass GW detector has three components [13]: a mechanical elastic solid antenna, an electromechanical transducer, and an electrical amplifier. The antenna can
be characterized by five parameters: effective mass $M$, effective length $D$, angular resonance frequency $\omega_0$, quality factor $Q_0$, and temperature $T_0$. Two types of resonant detectors exist today: cylinder bar detectors and spherical detectors. Another type, the dual detector, is now under study [14]. Several groups around the world operate cylinder bar detectors, namely ALLEGRO (Louisiana, USA), EXPLORER (CERN, Switzerland), NAUTILUS (Rome, Italy), and AURIGA (Padova, Italy). In the next section we will describe the AURIGA detector in more detail.

In 1993 Johnson and Merkowitz discovered the TIGA (Truncated Icosahedron Gravitational wave Antenna) configuration, solving the main problem for gravitational wave detection with a sphere. Not much later several projects for building spherical detectors were proposed [6]. The first spherical detector that has been built is MiniGRAIL (Leiden, The Netherlands), two other spherical detectors are being developed and are SFERA in Rome, Italy and SCHENBERG in Sao Paolo, Brazil. An advantage of spherical detectors is their omni-directionality.

The MiniGRAIL detector (see figure 2.9) is a cryogenic 68 cm diameter spherical gravitational wave detector made of CuAl6% alloy with a mass of 1400 Kg, a resonance frequency of 2.9 kHz and a bandwidth of around 230 Hz. The strain spectral sensitivity $\sqrt{S_{hh}}$ is at present about $1.5 \cdot 10^{-20}$. The antenna will eventually operate at a temperature of 20 mK. The sources that are aimed at are for instance non-axisymmetric instabilities in rotating single and binary neutron stars and small black-hole or neutron-star mergers [9].

![Figure 2.9: Drawing of the experimental setup of the spherical gravitational wave detector MiniGRAIL, Leiden, The Netherlands. See [9].](image)
2.4 Gravitational wave bar detector AURIGA

The gravitational wave bar detector AURIGA is located in the Laboratori Nazionali di Legnaro near Padova, Italy, which is a part of the Istituto Nazionale di Fisica Nucleare. It consists of an aluminum alloy (Al5056) bar of 3 meter length, a cross section of 60 cm and a mass of 2.3 tons (figure 2.10). The speed of sound in Al5056 is about 5.4 km/s, which means that the 3 meters long bar has a first longitudinal resonance mode at 920 Hz at cryogenic temperatures. The material is chosen as a compromise of good mechanical properties and practical feasibility. An important property of the material is its high mechanical quality factor (Q). The AURIGA bar has a Q of about $4 \cdot 10^8$ at 100 mK.

![Figure 2.10: Picture of the bar made of Al5056 as it is placed inside the cryostat. The bar is suspended from its center of mass and is supported by an attenuation system of 4 mass-spring columns (partly visible). On the bar end face a resonant capacitive transducer is also visible (see also section 3.1). Picture from [15].](image)

The sensitivity of the detector is highest when the gravitational wave propagates perpendicular to the bar’s longitudinal axis and has frequency components at the longitudinal resonant frequency of the bar. The energy from such a passing gravitational wave that is stored in the bar is proportional to the bar cross section $\Sigma$. If the wave arrives perpendicularly to the bar’s longitudinal axis, having linear polarization optimally aligned with the bar, the cross section $\Sigma$ is given by:

$$\Sigma = \frac{16G}{\pi c^3} M_b L_b^2 \omega_b^2$$  \hspace{1cm} (2.8)
with $G$ the gravitational constant, $c$ the speed of light, and $M_b$, $L_b$ and $\omega_b$ respectively the bar’s mass, length and resonant angular frequency. This means for AURIGA that in such a case the cross section is $\Sigma = 9 \cdot 10^{-25} \, m^2 Hz$. The goal is to be able to detect a relative length change $\delta h$ of the bar, which is defined as $\Delta L/L$ (with $\Delta L$ the total length change of the bar, so the displacement of each bar end face would be $\Delta L/2$), of the order of $10^{-20}$. A schematic view of the bar detector is given in figure 2.11.

![Mechanical suspension](image)

Figure 2.11: The sensitivity of the bar detector depends on the direction of propagation of the gravitational wave. If this direction is perpendicular to the bar’s longitudinal axis, the sensitivity is highest. In the picture this would be the case if $\theta = \pi/2$ or $\theta = 3\pi/2$. Picture from [15].

Since the sensitivity of the detector depends linearly on the ratio $Q/T$ of the mechanical quality factor and the temperature, the temperature should be as low as possible. Also, at low temperature the $Q$ is a few orders of magnitude higher. Therefore the bar is cooled to cryogenic temperatures down to 100 mK. To do this the bar is placed inside a cryostat equipped with a $^3$He-$^4$He dilution refrigerator and a number of thermal shields.

When a gravitational wave hits the bar, it induces a bar vibration. The amplitude of oscillation is biggest at the bar end faces. Therefore on one of the bar end faces a resonant transducer is placed to amplify and readout the vibration signal. At this moment AURIGA is equipped with a resonant capacitive transducer coupled to the bar having its fundamental mode of resonance at the same frequency as the bar. It is described in more detail in section 3.1. This transducer converts the mechanical signal into an electrical one, which is then via an impedance matching transformer amplified by a SQUID amplifier (see also section 3.1).
Chapter 2: Gravitational Waves, Sources and Detectors

The sensitivity of the AURIGA detector during its second scientific run, which started in November 2003 and is presently still in progress, is given in figure 2.12. The given graph displays the strain spectral sensitivity $\sqrt{S_{hh}}$ as it was in December 2004.

Figure 2.12: Sensitivity of the AURIGA detector in December 2004, at a temperature of 4.5 K. The different noise sources are displayed, which together determine the antenna’s sensitivity [15].
Chapter 3

The Optical Transducer

3.1 Transducers for resonant detectors

To amplify mechanically the oscillations of a resonant antenna (induced by a passing gravitational wave) and to convert this mechanical signal into an electromagnetic signal, a so called resonant transducer is used. Essentially, from a mechanical viewpoint, a resonant transducer consists of a secondary resonator coupled to the main resonator (i.e. the antenna) and tuned to it: since the transducer is much lighter than the main resonator, a mechanical amplification is obtained (see below). One can distinguish between active and passive transducers [13]: in a passive transducer the electromechanical coupling is obtained by means of a dc electric or magnetic field. The electrical output signal frequency \( \omega' \) is then equal to the mechanical input signal frequency \( \omega \). Various types of passive transducers have been developed over the years, of which the most common are the capacitive transducer and the inductive transducer.

In an active transducer, the coupling is obtained by applying an ac electromagnetic field at a pump frequency \( \omega_p \gg \omega \). The output signal then appears at the two sidebands \( \omega' = \omega_p \pm \omega \). Examples are transducers that make use of a balanced [16] or stabilized [17] microwave cavity, or a stabilized Fabry-Perot cavity [18]. In general, the frequency stabilization and demodulation stages introduced complicate the design and operation of an active transducer compared with a passive one. An active transducer however has the advantage of frequency upconversion and parametric gain, which can effectively reduce the amplifier noise.

An active transducer is now being developed at the Laboratori Nazionali di Legnaro in Italy; it is an optical transducer, which makes use of Fabry-Perot cavities. It is to be used for AURIGA, and is the main subject of this thesis. Tests of this optical transducer on a room temperature bar have already been done [1], and tests at cryogenic temperatures (4.2 K) are planned for the near future.

In this section a short description of the two aforementioned (already existing) passive transducers will be given (sections 3.1.1 and 3.1.2), after which the working principle of the optical transducer for AURIGA will be explained (section 3.1.3).
3.1.1 The capacitive transducer

Most of the resonant (cylindrical and spherical) detectors of today make use of one or more capacitive transducers, coupled to a (double-stage) SQUID amplifier (Superconducting QUantum Interference Device), see for example [19]. Also in AURIGA a capacitive transducer is used [20], [31], tuned to the first resonant mode of the bar at around 900 Hz, together with a double stage SQUID amplifier. The transducer, shown schematically in figure 3.1, is attached to one of the two end faces of the bar (figure 3.2).

At the other side of the bar a calibrator (i.e. a capacitive transducer but resonating at a higher frequency than the bar and resonant transducer) is attached to keep the bar in balance (the bar is suspended horizontally at its centre of mass, see chapter 2) and to provide a means to mechanically excite the bar for a force calibration.

![Schematic representation of the bar and capacitive transducer of AURIGA](image)

The transducer and the bar form a system of two well-matched high-Q coupled oscillators. The transducer, which is a plane plate capacitor, is an Al5056 "mushroom" shaped device, see figure 3.3. When the bar end face vibrates, this vibration is passed onto one of the two parallel plates of the transducer, mechanically amplified by a factor $\frac{m_b}{m_t}$ where $m_b$ is the bar effective mass, and $m_t$ the transducer effective mass.

The changing distance between the capacitor plates induces an electrical signal. This signal is applied to the input coil of a dc SQUID amplifier by means of a
superconducting matching transformer, which provides the required impedance matching (see figure 3.1).

A SQUID is a very sensitive device which can convert a magnetic field flux into a voltage. In AURIGA a double stage SQUID amplifier is used [20], consisting of two quantum design dc SQUIDS. Also MiniGRAIL has a double stage SQUID system [19]: the first is the sensor SQUID, the second is a DROS (Double Relaxation Oscillation SQUID) [31] that works as a cryogenic pre-amplifier.

![Figure 3.2: View of the bar end face with the capacitive transducer, the transformer and the SQUID box [15].](image)

![Figure 3.3: Drawing of the AURIGA capacitive transducer. The lower part of the transducer is the resonator which is directly bolded to the bar end face. The capacitor plate co-moving with the bar is here indicated as charged plate. A teflon (PTFE) spacer guarantees the electrical insulation between the two plates [15].](image)
3.1.2 The inductive transducer

The inductive transducer (usually) consists of two or three stages: one or two mechanical stages and an electromagnetic stage. The mechanical amplifier(s) is (are) tuned to the same frequency as the detector, and together they act as a two (three) mass-spring system. The last stage, which is electromagnetic, consists of a superconducting coil with a persistent current running through it. This last stage is then coupled to a (double-stage) SQUID amplifier.

An inductive transducer consisting of one mechanical stage and an electromagnetic stage is used in the gravitational wave bar antenna ALLEGRO, Louisiana, USA [21]. Another inductive transducer, consisting of two mechanical stages and an electromagnetic stage, is being developed for the spherical gravitational wave antenna MiniGRAIL in Leiden, The Netherlands [19], [6]. A schematic view of its design is given in figure 3.4.

A minor part of the work for this thesis was done at the MiniGRAIL site in the Kamerlingh Onnes Laboratory, Leiden University, The Netherlands, and regarded development and mechanical quality factor measurements of the second (mechanical) stage of this inductive transducer, which is an Al5056 resonator with a Niobium (Nb) layer on top, described below.

![Figure 3.4: Schematic representation of a three mode inductive transducer, as is being developed for the spherical gravitational wave antenna MiniGRAIL in Leiden, The Netherlands [6].](image-url)
Chapter 3: The Optical Transducer

The first mechanical stage of the MiniGRAIL inductive transducer is a rosette shaped CuAl6% resonator, with a central oscillating mass of about 30 g. The mass is connected to an external body of about 300 g using three half ring shaped springs. This external body is clamped inside a hole in the sphere. The second mechanical stage is as mentioned before an Al5056 resonator, see figure 3.5. It consists of a disk of 33.2 mm in diameter, thickness 0.7 mm and an effective mass of 1.5 g. Four s-shaped springs of 1 mm thickness support this disk and connect it to a conical base.

**Figure 3.5:** Close-up of the Al5056 resonator. Four springs sustain the top plate, which is covered with a Niobium layer of 500 nm [22].

This conical base is clamped into the inner ring of the 1st (CuAl6%) resonator, using thermal contraction techniques. Figure 3.6 shows the Al5056 resonator assembled into the CuAl6% resonator.

**Figure 3.6:** The two mechanical amplification stages of the inductive transducer. The Al5056 resonator (which is the 2nd stage) is clamped into the rosette shaped CuAl6% resonator (1st stage) using thermal contraction techniques [22].

Eight of these Al5056 resonators were machined and tested with respect to their surface flatness and mechanical quality factor at room temperature. We took the resonator with the highest Q and flattest surface to test and treat further. Different methods were tried to polish the top surface of the top plate. Eventually it was flattened within approximately 3 µm with a high precision lathe, after which it was polished using diamond paste of decreasing grain size.

A flat surface was important because of a Nb layer of 500 nm that had to be deposited on top of it. To be able to deposit this layer, the surface of the resonator was polished to a roughness of 200 nm. The layer was deposited because of the fact that Nb has a higher critical magnetic field than Al5056. This high critical field value is necessary because at a distance of 20 µm from the top plate (plus Nb layer) a superconducting coil is placed, in which a persistent current of 5-8 A runs that induces a magnetic field. Vibrations of the Al5056 top plate will influence this magnetic field, and thus the current in the coil: a time dependent current signal will be added to the constant current. The magnetic field however, should not enter the Al5056 resonator, because then it is not deformed in the desired way so as to induce an additional current in the
Chapter 3: The Optical Transducer

coil. A Nb layer with a high critical field prevents the field from penetrating the Al5056. The superconducting coil is shown in figure 3.7.

![Figure 3.7: Superconducting coil that picks up the changes in the magnetic field. The coil has 39 windings of 200 μm wide, separated 200 μm. The diameter of the coil is 33 mm. The U-shape is a superconducting shortcut of 10 mm, used to trap the current. The fabrication, working principle and testing of the coil at 4.2 K is described in [22].](image1)

The current signal is then passed on to a double stage SQUID, which makes read out with room temperature electronics possible. A cross sectional view of the used configuration of the three stages of the inductive transducer is depicted in figure 3.8.

![Figure 3.8: Cross section schematical view of the three-mode inductive transducer as is being developed for MiniGRAIL [19].](image2)

The deposition of the Nb layer, thickness 500 nm, we did at the University of Twente (Enschede, The Netherlands), where a DC sputtering system is available. An Aluminum layer of 5 nm was deposited on the top plate before the sputtering of the Nb layer, to increase the adhesion of the Nb layer and to smoothen further the surface. After sputtering the Nb layer, we added another Aluminum layer of 5nm, to protect the Nb layer from oxidation.
To test the mechanical Q, the Al5056 resonator was press fitted into the conical hole of a CuAl6% test mass, using three Al5056 screws to improve the clamping further. We lead-tin plated this CuAl6% test mass using a home made electrolytic deposition facility, consisting of a lead-tin fluoroborate bath and electrodes of a Pb40Sn60 alloy. A layer of lead-tin, about 60 µm thick, was deposited on the whole support surface. Together with a lid of CuAl6%, also lead-tin plated, where the silicon wafer with the coil is placed, it forms a superconducting shield for future measurements with the resonator, the coil and the SQUID. In the mechanical Q measurements performed here however the lid was not assembled.

A special 4 K test facility (at the MiniGRAIL site) was used to measure the mechanical Q of the second stage Al5056 resonator before and after depositing the Nb layer, in order to determine the influence of the sputtering. The Q was measured using two piezoelectric transducers (PZT) glued to the Al5056 resonator base: one for the excitation and another for readout. As can be seen in table 3.1 we found the Q of the main mode of resonance to be \((1.35 \pm 0.05) \cdot 10^6\) at a frequency of 3269.23 Hz before and \((1.00 \pm 0.05) \cdot 10^6\) at a frequency of 3264.7 Hz after the deposition of the Nb layer. So the reduction of the Q was about 25%. Also the Q at a second mode, which is a flexural mode of resonance (see for an explanation [19]), was measured and is given in table 3.1. This mode however is not of interest to us because only the main mode (at around 3265 Hz) couples to the sphere and is used for readout. This main mode concerns motion of the top plate in a direction perpendicular to its surface, and is called the transducer mode.

**Table 3.1: Mechanical Quality Factor of the Al5056 resonator before and after deposition of a 500 nm Nb-layer. These measurements were done at a pressure of \(p = 1 \cdot 10^4\) mbar, at a temperature of 4.2 K.**

<table>
<thead>
<tr>
<th>Before deposition of Nb-layer</th>
<th>After deposition of Nb-layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v) (Hz)</td>
<td>(Q)</td>
</tr>
<tr>
<td>3269.23</td>
<td>((1.35 \pm 0.05) \cdot 10^6)</td>
</tr>
<tr>
<td>6269.53</td>
<td>((1.40 \pm 0.05) \cdot 10^6)</td>
</tr>
</tbody>
</table>

As can be seen in table 3.1, the decrease in Q factor is higher for the flexural mode than for the transducer mode. This is because the flexural mode concerns bending of the surface itself, and the Nb layer has a larger influence on this movement than on the vertical movement in the transducer mode.

For further developments and measurements on the inductive transducer (for example on the Al5056 resonator together with the coil), as well as for the capacitive transducer and the double stage SQUID system for MiniGRAIL, see [19].

### 3.1.3 The optical transducer

The vast improvements that have been made in recent years in the fabrication of optical devices mean better possibilities for the development of an optical transducer for gravitational wave detection. Such an optical transducer is now being developed for the gravitational wave bar detector AURIGA at the Laboratori Nazionali di Legnaro, Italy.
Chapter 3: The Optical Transducer

With this transducer the bar vibration is detected by means of a resonant optical cavity called a Fabry-Perot cavity (see section 3.2), formed between the bar and a mechanical resonator which is attached to one of the bar end faces. A Fabry-Perot cavity is made of two parallel high reflectivity mirrors facing each other. When the mirrors are a distance $n\lambda/2$ apart, where $n \in \mathbb{N}$ and $\lambda$ the wavelength of the laser, the cavity is said to be at resonance and a laser beam bounces back and forth between the mirrors.

One of the mirrors is fixed to the bar while the other to the resonant transducer. A bar vibration induces a time-varying relative displacement between bar and transducer. In this way the length of the Fabry-Perot cavity is modulated, and thus its optical resonance frequency changes. The relative displacement $\Delta l$ of the two mirrors gives a change in resonance frequency given by:

$$\frac{\Delta l}{L_c} = \frac{\Delta \nu}{\nu_0} \quad (3.1)$$

Here $L_c$ is the length of the Fabry-Perot cavity and $\nu_0$ its resonance frequency. Thus, by determining the change in resonance frequency one can obtain the length change of the cavity, possibly induced by a gravitational wave. By means of a feedback loop, making use of the FM-sidebands technique (section 3.3), this change in frequency is followed by the laser source, thus maintaining optical resonance in the cavity. A schematic representation of the system of bar, transducer and cavity between them, is given in figure 3.9.

Figure 3.9: Equivalent scheme of the bar and the transducer with in between the Fabry-Perot transducer cavity. The system of bar and transducer can be characterized as two coupled harmonic oscillators. When a gravitational wave, with frequency components at the resonance frequency of the antenna, hits the bar, the bar end face will undergo a displacement $x(t)$. This displacement is passed on to the transducer to give it a displacement $y(t)$, amplifying the amplitude of vibration by a factor of $\frac{m_b}{m_t}$, with $m_b$ the effective mass of the bar and $m_t$ the effective mass of the transducer; $k_b$ and $k_t$ are the elastic constants of respectively the bar and the transducer, $b_b$ and $b_t$ are the damping of respectively the bar and the transducer [23].

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A schematic drawing of the optical readout setup is given in figure 3.10. The beam, being produced by a Continuous Wave Nd:YAG laser source with a wavelength of 1064 nm (near IR) and a power of 50 mW, is phase modulated and power stabilized before it hits a beam splitter. One part of the beam is reflected towards a reference cavity; the other part of the beam goes through the beam splitter and, via an optical fibre, reaches the transducer cavity. If the transducer cavity located in the cryostat and formed between the bar and the resonator, changes in length, it is no longer in resonance. The laser beam then does not (entirely) enter the cavity, but is reflected by it; only in resonance the laser enters (see section 3.2). In this way, with the FM sidebands technique (see section 3.3), an error signal is obtained. Via a locking feedback loop, headed by the error signal, the laser source frequency is then adjusted and locked to the transducer cavity. In this way the laser source will follow the transducer cavity in frequency.

Figure 3.10: Scheme of the optical readout setup [15].

The beam reflected by the beam splitter impinges on the reference cavity, which is used to compare the laser frequency to a reference frequency. This cavity has to have a very stable optical resonance frequency, so that the fluctuations around the frequency of interest (around 1 kHz) are smaller than those coming from the transducer cavity that we want to read out. The cavity thus has to maintain very precisely its length. To this end the cavity is actively held at a constant temperature by a temperature control with temperature variations kept below 1 mK; mechanical and
acoustic noise is damped around 1 kHz by placing the cavity in a vacuum chamber and mounting it on a double stage mechanical suspension.

The reflected beam of the reference cavity is collected by a photodiode and, again with the FM-sidebands technique, an error signal is obtained. Because of the laser beam being locked to the transducer cavity, this error signal is proportional to the difference between the (optical) resonance frequency of the transducer cavity and the (optical) resonance frequency of the reference cavity. Since we have relation (3.1), this signal is also proportional to the variation in length of the transducer cavity. In this way it is possible to determine the length change in the transducer cavity, which possibly carries a gravitational wave signal with it.

### 3.2 Fabry-Perot cavity

The Fabry-Perot cavity was first developed by the French physicists Charles Fabry and Alfred Perot at the University of Marseilles in the late 19th century and made use of interference of light reflected many times between two lightly-silvered mirrors. A theoretical discussion of such an interference pattern had been developed many years earlier by the British astronomer George Airy, but its implementation by Fabry and Perot proved to be a tremendous breakthrough in precision measurement (metrology) and wavelength comparisons in spectroscopy. Fabry-Perot interferometers are used today in both of these fields, as well as in atomic and optical physics, where Fabry-Perot cavities can be used to ensure precise tuning of laser frequencies.

A Fabry-Perot cavity [24], [32] consists of two partially reflecting parallel mirrors facing each other. In our case one of the mirrors is flat, the other one is concave. A schematic picture of a FP-cavity is given in figure 3.11.

![Figure 3.11: Fabry-Pérot Cavity with incoming ($\Psi_0$), reflected ($\Psi_r$) and transmitted ($\Psi_t$) electrical fields. The field inside the cavity is $\Psi_c$. The cavity has a flat mirror M1 and a concave mirror M2, and a cavity length $L_c$ [23].](image-url)
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The electromagnetic field is labelled in figure 3.11 by $\Psi$. When a beam, i.e. an electromagnetic field, described by $\Psi_0$, arrives at the cavity, it is partially reflected and partially transmitted by the first mirror $M1$ (assuming zero losses). The transmitted part enters the cavity and reaches the second mirror $M2$, and is partially transmitted and partially reflected again. The reflected part arrives again at mirror $M1$ and so on. Adding all contributions in this way we obtain the field $\Psi_c$ inside the cavity. The relation of $\Psi_c$ and $\Psi_0$ can then be expressed as:

$$t_1 \Psi_0 = (1 - r_1 r_2 e^{2i\delta}) \Psi_c$$

(3.2)

with $\delta$ the phase shift that the wave undergoes when it travels a distance $L_c$ (the length of the cavity) given by:

$$\delta = \frac{2\pi v_i n L_c}{c}$$

(3.3)

Here $v_i$ is the resonance frequency, $n$ the refraction index of the medium inside the cavity, and $c$ the velocity of light. The (amplitude-) transmission coefficient of the $i^{th}$ mirror is denoted $t_i$. The (amplitude-) reflectivity coefficient of the $i^{th}$ mirror is $r_i$. We define the transmittivity as $T_i = t_i^2$ and the reflectivity $R_i = r_i^2$. If we indicate the loss at the $i^{th}$ mirror as $p_i$ we get:

$$T_i + R_i + p_i = 1$$

(3.4)

The total transmitted field $\Psi_t$ and reflected field $\Psi_r$ of the cavity are:

$$\Psi_t = t_2 \Psi_c e^{i\delta}$$

(3.5)

$$\Psi_r = r_1 \Psi_0 - t_1 r_2 \Psi_c e^{2i\delta}$$

(3.6)

Using (3.2) we can solve (3.5) and we get for the transfer function $H$:

$$H_t(\delta) = \frac{\Psi_t}{\Psi_0} = \frac{t_1 t_2 e^{i\delta}}{1 - r_1 r_2 e^{2i\delta}}$$

(3.7)

$$H_r(\delta) = \frac{\Psi_r}{\Psi_0} = \frac{r_1 - r_2 (r_1^2 + t_1^2) e^{2i\delta}}{1 - r_1 r_2 e^{2i\delta}}$$

(3.8)
To get the intensity of the reflected and of the transmitted beam we take the square modulus of $H$:

\[
I_r = I_0 \frac{T_1 T_2 n_r^2}{1 + B \sin^2 \delta} \tag{3.9}
\]

\[
I_r = I_0 \frac{\xi^2 + (1 - p_r) B \sin^2 \delta}{1 + B \sin^2 \delta} \tag{3.10}
\]

Here we used $n_r$ (which represents the number of bounces that the beam makes inside the cavity before it exits), $B$ and $\xi$ which are defined by:

\[
n_r = \frac{1}{1 - r_2 r_2}, \tag{3.11}
\]

\[
B = \frac{4 r_1 r_2}{(1 - r_1 r_2)^2}, \tag{3.12}
\]

\[
\xi = r_1 - \frac{r_2 T_1}{1 - r_1 r_2}. \tag{3.13}
\]

When $\delta$ equals an integer times $\pi$, that is any time when

\[
\delta = \frac{2\pi v_i n L_c}{c} = k\pi \tag{3.14}
\]

where $k$ is a natural number, the cavity is said to be at resonance, and $\sin^2 \delta = 0$. This means, as can be seen from (3.10) that the intensity of the transmitted field reaches its maximum, and the intensity of the reflected field has its minimum. Obviously then $\xi^2$ represents the fraction of the incoming intensity that is being reflected by the cavity at resonance. The ratio between the transmitted intensity and the incoming intensity as a function of $\delta$ is plotted in figure 3.12. The ratio between the reflected intensity and the incoming intensity as a function of $\delta$ is plotted in figure 3.13.

---

**Figure 3.12:** Transmitted intensity for three different cavities, normalized to incident intensity. Thickest curve: $T_1=150\text{ppm}$, $T_2=10\text{ppm}$. Intermediate curve: $T_1=150\text{ppm}$, $T_2=50\text{ppm}$. Thinnest curve: $T_1=150\text{ppm}$, $T_2=500\text{ppm}$. For all curves $p_1= p_2=5\text{ppm}$. 

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Figure 3.13: Reflected intensity for three different cavities, normalized to incident intensity. Thickest curve: $T_1=150$ ppm, $T_2=10$ ppm. Intermediate curve: $T_1=150$ ppm, $T_2=50$ ppm. Thinnest curve: $T_1=150$ ppm, $T_2=500$ ppm. For all curves $p_1=p_2=5$ ppm.

The phase shift of the incoming and the reflected beam as a function of $\delta$ is shown in figure 3.14.

The curve of the ratio of the transmitted intensity and the incident intensity is called Airy curve, and it has maxima for $\delta = k\pi$, with $k$ an integer number. At these maxima the cavity is at resonance. The difference in frequency between two maxima is called the Free Spectral Range (FSR):

$$FSR = \frac{c}{2L_c} \quad (3.15)$$

In figure 3.15 a graph is shown of the transmitted intensity against the frequency, to illustrate the FSR.
Figure 3.15: Peaks of the transmitted intensity, which are separated by a distance in frequency called the Free Spectral Range.

The width $\Delta \nu$ at half the height of the resonance peaks of figures 3.15, is given by:

$$\Delta \nu = \frac{c}{2 \pi L} \frac{1 - r_1 r_2}{\sqrt{r_1 r_2}} = \frac{c}{\pi L} \frac{1}{\sqrt{B}}$$  \hspace{1cm} (3.16)

An important characterization of a Fabry-Perot cavity is through the Finesse $F$, defined as the ratio between the FSR and $\Delta \nu$:

$$F = \frac{FSR}{\Delta \nu} = \frac{\pi \sqrt{r_1 r_2}}{1 - r_1 r_2} = \frac{\pi \sqrt{B}}{2}$$  \hspace{1cm} (3.17)

### 3.3 FM-sidebands technique for laser frequency locking

The FM-sidebands technique, also known as the Pound-Drever-Hall technique, is widely used to stabilize laser sources by locking them to a Fabry-Perot cavity. In our case it is used to make the frequency of the laser follow the (changing) resonance frequency of the transducer cavity. This is done by extracting an error signal which is proportional to the difference in frequency of the cavity and the laser: $\nu_c - \nu_l$. The error signal is used in a feedback loop (servo-loop) to adjust the laser frequency in order to annihilate the error signal. In this way the Fabry-Perot cavity can be kept in optical resonance, because the laser frequency follows the cavity resonance frequency. A schematic view of the Pound-Drever-Hall locking circuit is given in figure 3.16.
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Figure 3.16: Schematic view of the working principle of the Pound-Drever-Hall locking circuit [25].

Coming from the laser source, we have a beam:

$$\psi(t) = \psi_0 e^{i(\omega_0 + \Delta\omega)t}$$  \hspace{1cm} (3.18)

This is a plane wave, where $\Delta\omega = \omega_\text{l} - \omega_\text{c}$ is the difference between the laser frequency $\omega_\text{l}$ and an optical resonance frequency $\omega_\text{c}$ of the cavity. First, after leaving the source, the laser beam is phase modulated at a frequency $v_m = Q/2\pi$, which must be much larger than the peak width $\Delta v_c$ (see figure 3.15), but much smaller than the FSR of the cavity:

$$\Delta v_c << v_m << \text{FSR}$$  \hspace{1cm} (3.19)

This is done to make sure that the sidebands never have the same frequency as a resonance of the cavity. This modulated beam reaches the cavity, and is partially reflected. The electric field incident on the cavity has three components: the carrier with frequency $\omega/2\pi$, and two sidebands with frequencies $(\omega \pm Q)/2\pi$. We thus get:

$$\psi(t) = \psi_0 e^{i(\omega_\text{l} + \Delta\omega + \beta \cos \Omega t)}$$  \hspace{1cm} (3.20)

where $\beta$ is the index of phase modulation. If we develop this expression up to the first order in Bessel functions we get:

$$\psi(t) = \psi_0 e^{i(\omega_\text{l} + \Delta\omega)} (J_0(\beta) + iJ_1(\beta)e^{i\Delta\omega} + iJ_1(\beta)e^{-i\Delta\omega})$$  \hspace{1cm} (3.21)

where $J_0$ and $J_1$ are Bessel functions. This approximation is valid for small $\beta$. 

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As we saw in equation (3.8), only the part \( H_r \) of each component is reflected by the cavity, and the expression for the reflected beam becomes:

\[
\psi(t) = \psi_0 e^{i(\omega_t + \Delta \omega)} \left[ J_0(\beta) H_r(\omega_0 + \Delta \omega) + iJ_1(\beta) e^{i\Delta \omega} H_r(\omega_0 + \Delta \omega + \Omega) + iJ_1(\beta) e^{-i\Delta \omega} H_r(\omega_0 + \Delta \omega - \Omega) \right] \tag{3.22}
\]

This reflected beam goes to a circulator (namely, a polarizing beam splitter followed by a quarter-wave plate) and is collected by a photodiode. If we take the square modulus of the field incident on the photodiode, we have its intensity. The current that the photodiode develops is proportional to this intensity. It thus has a DC component and components at frequencies of \( \Omega \) and \( 2\Omega \).

The signal is then sent to a Mixer with gain \( \chi \), which demodulates the signal with a signal coming from the Oscillator. In fact this demodulation signal is the same as the first modulation signal, only phase shifted (see figure 3.16). After the Mixer the signal has components at the first harmonics of \( \Omega \) and a DC component. From the Mixer, the signal is sent to a Low-pass Filter, to separate the DC-component, which actually represents the error signal.

In figure 3.17 the in-phase component of the error signal as a function of the frequency difference \( \Delta \nu = \nu_l - \nu_c \) between the laser and the cavity is shown. Near resonance the voltage signal follows a linear behaviour according to:

\[
V = -8\sqrt{2} \chi \eta R_f P_0 J_0(\beta) J_1(\beta) (1 - \xi) \frac{L_c F}{c} \Delta \nu \tag{3.23}
\]

where \( \chi \) is the gain of the Mixer, \( \eta \) the photodiode’s efficiency in A/W, \( R_f \) the resistance that the photodiode current sees, \( P_0 \) the power of the incident beam, \( F \) the cavity Finesse, and \( L_c \) the cavity length.

![Figure 3.17: Error signal as a function of the frequency difference between the laser and the cavity, for \( F = 1 \cdot 10^4 \), \( L_c = 20cm \) and \( \Omega = 5 \text{ MHz} \) [26].](image)
3.4 Noise sources and sensitivity

3.4.1 Introduction

In order to be able to predict the sensitivity of the entire system of resonant bar plus transducer, the various noise sources must be analyzed and estimated. Then all these noise types must be added up to obtain the total noise. For a resonant bar antenna like AURIGA we can distinguish between wide-band noise and narrow-band noise.

Narrow band noise is noise originating from the first, resonant parts of the chain, so the antenna itself or the transducer. When we look at the output of the detector, this noise has also been multiplied by the transfer function $H$, and so, if flat in frequency at the input, it comes to lie in a very narrow band around the resonance frequency. Thermal noise (section 3.1.2) of the bar and the transducer is an example of a noise source that excites the two oscillators and therefore becomes narrow band at the output.

On the other hand, the noise which is added later undergoes only linear amplifications, and its frequency behaviour is not changed, and is therefore wide band. Electronic noise (section 3.1.5) is an example of such a noise.

Consider figure 3.18, which is an equivalent scheme of the bar and the transducer. Suppose a force $f_{gw}$ acts on the bar due to a passing gravitational wave [26]. Also other forces act on the system: the thermal noise force $f_{th}$ of the bar and the thermal noise force $f_{tt}$ of the transducer. We also have the back-action force $f_{BA}$ which comes from the amplifier and is always present in any system with an amplifier or readout.

![Figure 3.18](image)

**Figure 3.18:** The system of two coupled oscillators, being the bar and the transducer. $K_b$ and $K_t$ are the elastic constants of respectively the bar and the transducer. $\beta_b$ and $\beta_t$ are the damping of respectively the bar and the transducer. Here $x$ and $y$ are the (longitudinal) coordinates of the bar end face and transducer surface respectively. The effective mass $m_b$ of the bar is $M_b/2$, with $M_b$ its physical mass [7].
If we assume \( x \) and \( y \) to be respectively the (longitudinal) coordinates of the bar end face and transducer surface, we can now obtain the system of equations of motion:

\[
\begin{align*}
    m_b \ddot{x} + \beta_b \dot{x} + \beta_i (\ddot{x} - \ddot{y}) + K_b x + K_i (x - y) &= f_{gw} + f_{TB} + f_{Ti} - f_{BA} \\
    m_i \ddot{y} - \beta_i (\ddot{x} - \ddot{y}) - K_i (x - y) &= f_{BA} - f_{Ti}
\end{align*}
\]

(3.20)

where \( K_b \) and \( K_i \) are the elastic constants of respectively the bar and the transducer, and \( \beta_b \) and \( \beta_i \) are the damping of respectively the bar and the transducer. Also we have that \( \beta_i = \frac{m_i \omega_i}{Q_i} \) and \( K_i = m_i \omega_i^2 \), with \( m_i \) the effective mass, \( \omega_i \) the resonant angular frequency and \( Q_i \) the mechanical quality factor of the oscillator. In the frequency domain, so taking the Fourier Transform, and solving for the oscillators relative displacement \( X - Y \), we get:

\[
X(\omega) - Y(\omega) = \frac{m_i \omega_i^2}{D(\omega)} (F_{gw} + F_{TB}) + \frac{K_i + i \omega \beta_i}{D(\omega)} - \frac{(m_b + m_i) \omega_i^2}{D(\omega)} (F_{BA} + F_{Ti})
\]

(3.21)

where \( D(\omega) \) is the determinant of the homogeneous system of Fourier transforms of the equations of motion (3.20):

\[
D(\omega) = (-m_b \omega_i^2 + K_b + K_i + i \omega(\beta_b + \beta_i))(-m_b \omega_i^2 + K_i + i \omega \beta_i) - (K_i + i \omega \beta_i)^2
\]

(3.22)

If we write (3.21) in the form

\[
X(\omega) - Y(\omega) = T_b(\omega)(F_{gw} + F_{TB}) + T_i(\omega)(F_{BA} + F_{Ti})
\]

(3.23)

we have with \( T_b(\omega) \) and \( T_i(\omega) \) the transfer functions of respectively the bar and the transducer. We will now look at the different noise sources that act on the system.

### 3.4.2 Thermal noise

An important source of noise that acts at the beginning of the chain, so on the bar and the transducer, is the thermal noise, which is a white noise. It is caused by the thermal motion of the atoms of the antenna and transducer and has a stochastic nature. At temperature \( T \) of the oscillator it can be characterized as a noise force acting on the body:

\[
S_{Ti}(\omega) = 2k_bT\beta_i \quad i = b,t
\]

(3.24)
Here the \( k_b \) is the Boltzmann constant and \( \beta_i = \frac{m_i \omega_i}{Q_i} \) the damping constant with \( m_i \) the effective mass, \( \omega_i \) the resonant angular frequency and \( Q_i \) the mechanical quality factor of the oscillator as was mentioned at the beginning of this section. At the detector output this noise has been multiplied by the transfer function \( H \), and therefore lies in a narrow band around the resonance frequency. Thermal noise arising from outside the cryostat (like from electronic components etc.) can be reduced to a negligible level, and so are not taken into account here.

### 3.4.3 Back-action noise

The back-action noise force, which too is a white noise, is given by:

\[
S_{fsa} (\omega) = \left( \frac{2}{c} \right)^2 S_p
\]  

(3.25)

where \( c \) is the speed of light and \( S_p \) is the noise spectrum of light power inside the cavity. At the quantum level this back-action noise force is due to the fluctuations in the laser intensity causing a fluctuation in radiation pressure on the transducer-cavity mirrors. It is possible to reduce the laser intensity noise to the quantum level, see section 3.6 (For a more detailed description see [26] section 3.5). Given that \( P_{0,i} \) is the laser power incident on the transducer cavity, \( T_{i,1} \) the transmittivity of the input mirror power and \( F_i \) the transducer cavity finesse, \( \beta \) the amplitude of laser phase modulation, we have for \( S_p \) given by the Poisson statistics of the input beam:

\[
S_p (\omega) = \left( \frac{F_i^2 T_{i,1}^2}{\pi^2} \right) h \nu_i J_0(\beta)^2 P_{0,i}
\]  

(3.26)

So, using (3.26) in (3.25) we get for the minimal back-action noise force on the transducer:

\[
S_{fsa} (\omega) = \left( \frac{2F_i^2 T_{i,1}^2}{c \pi^2} \right) h \nu_i J_0(\beta)^2 P_{0,i}
\]  

(3.27)

The act of measuring inevitably causes a perturbation of the antenna, which exists in our case of the exciting of the transducer. The back-action term is significant only for the transducer, for the bar it is negligible. This is because the transducer is much lighter and thus also much more displaced by the back-action force than the bar. The back-action noise at detector output becomes, like the thermal noise, narrow band.
**3.4.4 Electronic noise**

The electronic noise is a noise that’s coming from the non-resonant part of the chain of transduction. There is the electronic noise of the feedback circuit that provides the locking (this noise however is negligible), and there is the noise of the photodiodes, which is a shot noise. The process in which electrons are liberated in the photodiodes is a Poissonian process, and this noise is, like the back-action in the previous section, unavoidable and again also white noise. The voltage noise that is developed at the photodiode is given by:

\[
S_v(\omega) = eIR_f^2
\]

where \( e \) is the electronic charge, \( I \) the average photodiode current and \( R_f \) the resistance that the photodiode current sees.

This expression converts (using 3.23) for the noise in frequency into:

\[
S_{Vr}(\omega) = \frac{e}{128\chi^2\eta P_{0,\lambda}} \cdot \frac{1-J_o(\beta)^2(1-\xi^2)}{J_o(\beta)^2 J_1(\beta)^2(1-\xi^2)} \left( \frac{c}{F_i L_i} \right) \]

where \( P_{0,\lambda} \) is the laser power incident on the transducer cavity, \( F_i \) the finesse and \( L_i \) the length of the transducer cavity, \( \eta \) the photodiode efficiency and \( \chi \) the mixer gain. This is an expression for the transducer cavity; for the (photodiode current of) reference cavity a similar expression is valid for the noise in frequency \( S_{Vr} \).

**3.4.5 Other noise sources**

Apart from the noise sources mentioned above there are other, not so easy to predict noise sources [26]. For example there could be noise coming from the optical fibres (used to send the beam into the cryostat to the transducer cavity), low frequency acoustic relaxations of the rods used for the sensing cavity or of the loaded PZT, noise due to optic misalignment, wavefront distortion, laser beam pointing fluctuation, local atmospheric pressure variations along the beam path in air, vibrations of optics. There’s also the effect of local heating of the bar and the transducer due to laser power transmitted and dissipated by transducer cavity mirrors. However these noise sources are expected or have been tested not to be dominant.

**3.4.6 Sensitivity**

To find the total noise, we have to sum all the separate contributions to the noise mentioned above. We then get, written in frequency noise:
S_{\text{total}} = \frac{V_l^2}{L_e} \left[ T_b(\omega) S_{T_b} \right]^2 + \left| T_c(\omega) \right|^2 \left( S_{J_{\text{eff}}} + S_{T_c} \right) + S_{V_i} + S_{V_r} \tag{3.28}

Usually performances of different gravitational wave detectors are compared in terms of the equivalent strain noise amplitude \( S_{\text{hh}} \) at the detector input that would produce the noise power spectrum observed at the output. This is expressed by:

\[
S_{\text{hh}}(\omega) = S_{\text{displ-out}}(\omega) \cdot \left( \frac{1}{2} m_b l_b \omega^3 \right)^{-2} \cdot \frac{m_b \omega^2}{D(\omega)} \tag{3.29}
\]

Sometimes the sensitivity is given in terms of the effective temperature \( T_{\text{eff}} \) which corresponds to the minimum energy change \( E_{\text{eff}} \) that is detectable:

\[
T_{\text{eff}} = \frac{1}{k_b} E_{\text{eff}} = \frac{1}{k_b} m_b l_b^2 \omega^2 h_{0,\text{min}}^2 \tag{3.30}
\]

Here \( h_{0} \) is the minimum amplitude that an impulsive gravitational wave needs to have so that it can be detected by the antenna with optical readout, with a Signal to Noise Ratio (SNR) of 1.

**Table 3.2: Parameters used to calculate the sensitivity of the optical transducer**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T )</td>
<td>0.1K</td>
</tr>
<tr>
<td>( Q_b )</td>
<td>( 5 \times 10^6 )</td>
</tr>
<tr>
<td>( Q_t )</td>
<td>( 5 \times 10^6 )</td>
</tr>
<tr>
<td>( l_t )</td>
<td>1cm</td>
</tr>
<tr>
<td>( P_{0,t} )</td>
<td>2mW</td>
</tr>
<tr>
<td>( \zeta )</td>
<td>-0.58</td>
</tr>
<tr>
<td>( F_t )</td>
<td>( 3 \times 10^5 )</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.72A/W</td>
</tr>
<tr>
<td>( M_b )</td>
<td>1150kg</td>
</tr>
<tr>
<td>( \nu_0 )</td>
<td>920Hz</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>1.064\mu m</td>
</tr>
<tr>
<td>( L_{\text{sens}} )</td>
<td>20cm</td>
</tr>
<tr>
<td>( P_{0,\text{sens}} )</td>
<td>5mW</td>
</tr>
<tr>
<td>( \zeta_{\text{sens}} )</td>
<td>-0.95</td>
</tr>
<tr>
<td>( F_{\text{sens}} )</td>
<td>( 4 \times 10^4 )</td>
</tr>
<tr>
<td>( \beta )</td>
<td>1rad</td>
</tr>
</tbody>
</table>

Using the values of table 3.2, which are the parameters as they will be for the low temperature antenna with optical readout, we can now calculate the sensitivity of the optical transduction chain in terms of \( T_{\text{eff}} \), which turns out to be about 2 \( \mu \)K. For \( h_{0} \) we have a theoretical value of \( h_{0} = 2 \times 10^{-20} \). In figure 3.19 a graph of the sensitivity, as is usually done expressed in \( \sqrt{S_{hh}} \), against frequency is shown.
3.5 The optical table

The optical equipment used for the optical transducer is largely placed on an optical table outside the cryostat. Here the reference cavity is placed and the FM sidebands technique is applied to extract the error signal. In figure 3.20 a drawing of the setup is given.

First after leaving the 50 mW Nd:YAG laser source, the beam goes through a two stage optical isolator which makes sure that no parts of the beam that are reflected by parts of the system can re-enter the laser source causing a diminishing in the performance. Next a half-wave-plate makes the polarization of the beam from a horizontal in a vertical one. Lens f1 focuses the beam and the Electro-Optic modulator EOM1 is used by a feedback loop that stabilizes the power of the beam at about 1 kHz. Then the Polarizer (Pol1) makes sure that the beam has vertical polarization, after which another EOM is placed. This EOM2 modulates the phase of the beam according to the FM sidebands technique (see figure 3.20). The two EOMs and Pol1 are placed in an aluminum box whose temperature is actively stabilized at 32º C, because the EOM’s performance depends heavily on the temperature.

Another polarizer (Pol2) is crossed which once more makes sure that the polarization is still vertical. The beam passes lens f2 and then reaches the first beam splitter (BS30%)1, which lets 30% of the beam through and reflects 70%. The transmitted part is collected by a photodiode, which is connected to an amplitude stabilizing feedback loop that acts on EOM1. This loop works to reduce the laser power noise around 1 kHz. and to take the noise to the quantum level. In this way the back-action noise level is determined by the Poisson statistics of the photons and not higher (see section 3.4.3).

Figure 3.19: Plot of the spectral density of the total noise $\sqrt{S_{hh}}$ referred at bar input [26].
The reflected beam (which is now power stabilized) passes half wave plate ($\lambda/2)_2$ that rotates the polarization in order to optimize the entrance in the following optical isolators. A second beam splitter (BS30%)$_2$ once more divides the remaining beam, the reflected part (which is 30%) going via an optical isolator (O.I.3) and two mirrors $S_5$ and $S_6$ to an optical fibre. It is this single mode polarization maintaining optical fibre that transports the beam to the inside of the cryostat, where the beam will eventually reach the transducer cavity.

Figure 3.20: Drawing of the setup on the optical bench outside the cryostat.
Chapter 3: The Optical Transducer

The 70% that is transmitted passes optical isolator O.I.2, half wave plate ($\lambda/2)_1$ and lens $f_3$ after which it is again split in two by polarizing beam splitter PBS$_1$. The PBS has the property that it transmits the part of the beam with polarization in the plane of incidence (so horizontal in our case), and reflects the part with polarization in the direction perpendicular to the plane of incidence (vertical). Actually with ($\lambda/2)_3$ we can control the power that is transmitted in the two orthogonal polarization directions. In this way we can make a beam that is either fully transmitted or fully reflected by PBS$_1$. When we let the beam be reflected at PBS$_1$ it will go toward the Zerodur Fabry-Perot cavity (we call it this way because of the material Zerodur out of which it is made, see [26]), which will be used as the reference cavity for the experiment with the antenna at cryogenic temperature (4 K). The path that is followed in case of transmission at PBS$_1$ leads to the Invar Fabry-Perot cavity (again named after the material of which it is made) which has been used as reference cavity for the optical transducer in the room temperature experiment [1]. We will not discuss this path here, since it is similar to the one leading to the Zerodur cavity.

Looking at the path of reflection after PBS$_1$, where the beam has a vertical polarization, we see the beam pass another half wave plate ($\lambda/2)_2$ which turns the polarization in a horizontal one. Consequently it gets transmitted at PBS$_2$ (since this PBS also transmits only horizontally polarized beams) after which it crosses ($\lambda/4)_1$. This quarter wave plate has its principal optical axis inclined at a 45° angle compared to the incoming wave, which means that it turns the beams polarization into a circular one. After this the beam passes a lens ($f_4$) and 2 mirrors (S$_1$ and S$_2$) that align it in an appropriate way for it to enter the Zerodur cavity.

The intensity of the transmitted beam for this Zerodur cavity is measured by photodiode PDTR4, which can be useful in the process of aligning the beam to the cavity. The beam being reflected by the cavity passes again the two mirrors (S$_1$ and S$_2$) and the lens ($f_4$) as well as ($\lambda/4)_1$ which now converts the polarization back from circular into linear (this time in vertical direction). This time the beam gets reflected by PBS$_2$, after which it reaches another photodiode (PDZ). This photodiode gives a current signal that is used by the feedback loop (described in section 3.3) to frequency-lock the laser to the (resonance frequency of the) cavity.

Thus in this case the laser frequency was not (yet) locked to the transducer cavity, as will be done later for the experiments with the low temperature bar, but to the Zerodur reference cavity (or the Invar cavity). This was done in order to perform some test measurements. Some small modifications, repositioning and outlining of a part of the optics on the optical table was done, as well as mode matching of the laser beam, which is a Gaussian beam (see [27] for Gaussian beams and optics), to the reference cavities. Mode matching is shaping the input beam so that its spot size and wavefront curvature ‘fit’ into the cavity in which the beam is injected (see [28] for techniques of mode matching a beam to a Fabry Perot cavity).
Chapter 4

Mechanical Quality Factor of the Resonant Transducer

4.1 Mechanical quality factor

The mechanical quality factor (Q) plays an important role in the noise (and thus the sensitivity) of the bar detector and the transducer: the higher the Q, the lower the thermal noise, because of the linear relationship between the power spectral density of the thermal noise and $T/Q$, where T is the thermodynamical temperature. By measuring the Q, it is possible to make an estimate of the thermal noise of the resonator, which is necessary to make a calculation of the expected sensitivity of the detector. The bar itself has a high mechanical quality factor of about $5 \times 10^6$ at 4 K.

The Q is a measure of how much energy is dissipated into heat during oscillation at resonance. A high Q means little dissipation, and thus a long time constant of oscillation. Also frictions between different parts of the detector (e.g. the bar, the transducer, wires) cause dissipation of energy and thus lowering of the Q. The bar and the resonant transducer (resonator) are made of a special aluminum alloy: Al5056. This is the standard material used for resonant gravitational wave bar detectors and consists of aluminum with impurities of Mg (5.0%), Mn (0.12%), and Cr (0.12%). The mechanical Q at 4 K of this material can be as high as $3.8 \cdot 10^7$, which is the main reason to choose this material.

In the experiments described in this report four cryogenic runs have been made to measure the Q (see section 4.7) of the Al5056 resonator at its first and second resonance mode. The tests have all been done in the cryogenic test facility (section 4.2) at LNL-INFN using an optical readout setup (section 4.4) and piezo electric actuators (section 4.5). For the 2nd run, the optical readout in the test facility was changed slightly, for the 3rd run modifications on the resonator itself were made. For the 4th run we assembled the Al5056 parts on top of the resonator that will eventually be necessary when the optical transducer is assembled for coupling to the bar. These
parts serve to couple the laser beam, coming from the optical table outside the Dewar, to the transducer cavity (see Chapter 3: The Optical Transducer). Also the effect of other variables was tested, for example the level of excitation and the number, type and position of the PZTs, which were changed before each new run. The measurements during each run were done at four different temperatures: room temperature, 77 K, 64 K, and 4 K.

The Q was determined by looking at the relaxation time τ, using $Q = \pi \nu \tau$, with ν the frequency of the resonant mode. Only for a few measurements at room temperature was the Q determined from the width of the resonance peak obtained by measuring the output amplitude as a function of the frequency around resonance. The results are shown in section 4.7.

### 4.2 The transducer test facility

The measurements of the quality factor of the Al5056 resonator were conducted in the cryogenic transducer test facility (TTF) of the AURIGA laboratory at the Legnaro National Laboratories of INFN (Italy), shown in figure 4.1. This test facility was built for testing the AURIGA transducers at cryogenic temperatures. It is provided with a cryogenic suspension in order to decouple the transducer from the environmental mechanical noise. The attenuation of this cryogenic suspension is about -150 dB in a broad frequency range between 800 Hz and 1100 Hz, with a maximum at 900 Hz of -175 dB in vertical direction.

![Transducer Test Facility](image)

**Figure 4.1**: Ultra cryogenic test facility at the AURIGA laboratory of the INFN [29].
Chapter 4: Mechanical Quality Factor of the Resonant Transducer

The TTF can be cooled down to (ultra)cryogenic temperatures in a few days, which makes it very useful for the numerous tests that need to be done on the transducers. With reference to fig.1, the blue outer vessel is called the Dewar, the orange vessel is the Inner Vacuum Chamber (IVC), see figure 4.2 for a better view. The Dewar has a volume of 150 liter and can be filled with liquid nitrogen or liquid helium to cool the system down. Four internal thermal shields allow to diminish the heat flow to the IVC further. It is possible to pump the Dewar to lower pressures, and in this way to control the temperature. When the Dewar is filled with liquid Nitrogen (at 77 K), a temperature of 64 K can be reached in this manner by pumping to a pressure of around 130 mbar.

Figure 4.1 shows the capacitive transducer at the bottom of the IVC, which can also be tested in the test facility; this was not done in these experiments however, instead we tested the resonator of the optical transducer (figure 4.2). The IVC, the attenuation stages and the Dewar are hanging from an aluminum honeycomb structured platform (figure 4.1), which is light and can support a heavy weight. This platform is on its turn sustained by four pillars of reinforced concrete. Between the honeycomb platform and the pillars, layers of Sylomer are placed to damp vibrations further. This Sylomer is a soft rubber spring material with high internal friction: it provides the first room-temperature isolation at low frequencies of 10-100 Hz (in vertical direction).

The vacuum chamber where the transducers can be tested at low temperatures is called the Inner Vacuum Chamber (IVC), see figure 4.2. This is a cylindrical steel vessel, weighing 150 kg, which contains four cryogenic attenuation stages, constructed of masses and springs, made of aluminum.

![Figure 4.2: Inner Vacuum Chamber (IVC) with the four attenuation stages (depicted here in purple), the three Al7075 rods (only two are shown) and the supporting Al5056 base (all in light blue), and the Al5056 resonator to be tested (in pink) [7].](image)

From the last of the four attenuation stages three Al7075 (ergal) arms are hanging, at 120 degree angles relative to each other, which hold an Al5056 cylindrical mass of 20
kg. On top of this supporting mass the resonator that was tested was mounted, fixed by four M16 aluminum screws, turned with a dynamometric key to 35 Nm.

To pump this IVC to low pressure (down to below $1 \times 10^{-5}$ mbar) a backing pump and a turbo pump are used. The IVC can also be temporarily filled with exchange gas at low pressure, to accelerate the cooling down of the IVC. On the center axis of the Dewar, from the top flange all the way through the four attenuation stages inside the IVC, a pipe runs to allow a laser beam to reach the resonator without being blocked, as to make an optical readout possible (see section 4.4). At the upper end of the tube a little Fused Silica window pressed to an O-ring seals off the vacuum of the IVC.

### 4.3 The resonator

Measurements were done on the mechanical quality factor of the Al5056 resonator, using an optical readout setup and Piezo-electric actuators (PZT). The resonator, which is schematically shown in figure 4.3, has a total mass of 5680 gram, and consists of an outer ring (used to fix the transducer to the bar or to its support in the test facility, mass 4420 gram), therein an elastic membrane (mass 120 g), and a central load (mass 1140 g).

![Figure 4.3: View from aside of the mechanical resonator. The z-axis is the axis of cylindrical symmetry.](image)

For later experiments the resonator was slightly modified: in the center of the upper surface a hole was made where a Fused Silica mirror (diameter 12.7 mm, height 6 mm) could be placed (see section 4.7.3). This hole is shown in figure 4.3 with the dotted line in the top center; the mirror that was then placed is depicted in blue. The mirror was held by a flange that was screwed onto the resonator, using very little force.

The oscillator has a first resonance mode at around 906 Hz at room temperature, when coupled to a mass of a few tens of kg. In this mode the central load moves up and down along the z-axis (see figure 4.4a). This mode is to be used for reading the bar vibration with an opto-mechanical readout.

At about 1474 Hz there is a second resonance mode (figure 4.4b), which is actually a doublet: it consists of two orthogonal components. These vibrations tilt the central load in two perpendicular directions.
Figure 4.4a and b: The first and the second resonance mode of the resonator, respectively at frequencies of 906 Hz (4.4a) and 1474 Hz (4.4b) at room temperature.

In figure 4.5 and 4.6 a PROMECHANICA simulation of the resonator vibration is shown. In figure 4.5 the first modes of resonance is depicted, in figure 4.6 the two components of the second mode are shown.

Figure 4.6: The two orthogonal components of the second mode (this mode is therefore called a doublet) at 1474 Hz at room temperature.
Previous measurements (on the room temperature bar [1]) showed for the first mode a resonance frequency corresponding to an oscillating mass of $1.70 \pm 0.02$ kg, while the mass of the central load plus the membrane is about 1.3 kg. The reason for this discrepancy is not well understood. The quoted frequencies refer to room temperature, and to the transducer attached to a 20 kg mass made of Al5056 (see figure 4.7). The value of the displacement of the central load can be inferred from the output signal of an accelerometer placed on it, see section 4.6 about the calibration.

![Figure 4.7: Resonator, supported by the 20 kg AL5056 base. The base is suspended by three rods from the last of the four attenuation stages of the test facility. Brass screws (M5) were used to fix the three rods and the base.](image)

### 4.3 The optical readout

The mechanical quality factor of the resonator was measured at different temperatures and pressures. We did so using an optical readout consisting of a laser, optical devices (lenses, mirrors, a beam splitter), a quadrant photodiode and some electronic circuits (at room temperature and atmospheric pressure measurements with accelerometers placed on the central load were also done). The optical configuration that we were using was first tested on a standard optical table outside the test facility in the AURIGA laboratory. This optical table gives the opportunity to easily change and test different configurations.
The laser beam was provided by a Nd:YAG Continuous Wave laser source (manufactured by Crystal) of 100 mW, wavelength 1064 nm (near IR), which had a filter in front of it diminishing the power to about 12 mW as to not saturate the final photodiode. The laser is placed on a little optical bench on top of the test facility. On this optical bench also the other optical components were placed (see figure 4.8).

![Image of optical bench](image)

**Figure 4.8:** Optical bench on top of the test facility. At the far end of the bench the laser (left) and the quadrant photodiode (right) are visible. The red line that is drawn is the path of the laser beam (see also fig. 4.9).

This optical bench is schematically drawn again in figure 4.9. Coming from the laser source the beam is reflected by mirror #1, then passes through lens a (focal length 25 mm) and is reflected by mirror #2. After going through lens b (focal length 300 mm) the beam arrives at a beam splitter, which splits the beam in a transmitted part and a reflected part. The reflected part goes to a tilted mirror (#3) which diverts the beam downwards into the test facility.

A little optical window (of Fused Silica) allows the beam to enter a long (about 1.5 m) and thin (diameter about 3 cm) tube leading to the resonator inside the Inner Vacuum Chamber (IVC). On the central load of the resonator a mirror is glued (see figure 4.12) which reflects the beam upwards again; the mirror is made of a reflective multilayer about 10 μm thick, coated on top of a Fused Silica substrate, diameter 0.5 inch, height 0.25 inch.
Figure 4.9: Optical path of the laser beam on the optical bench on top of the test facility. From the tilted mirror the beam goes down into the IVC through a 2 meters long tube (not drawn here), and is then reflected by a mirror on the resonator.

Because of the beam hitting this mirror under a small angle $\alpha$ (of about 0.2 degrees) relative to the normal, a vertical movement $S$ of the central load (holding the mirror) translates the beam, and thus makes it to return through the pipe slightly shifted (see figure 4.10). The angle plays an important role in the retrieved signal. If the angle is too small, the signal will be small too; but if the angle is too big, the laser beam will not pass through the window or will not hit the mirrors entirely anymore, or will hit the pipe.

Figure 4.10: A vertical displacement of the resonator-mirror, caused by the oscillation of the central load of the resonator, displaces the beam and makes it arrive at the photodiode shifted over a distance $d$. The angle $\alpha$ is about 0.2 degrees.
Reflected again by the tilted mirror (#3), the beam arrives again at the beam splitter. The transmitted part of the beam then is reflected by mirror #4, crosses 2 lenses (c and d) and is then detected by the quadrant photodiode. It is the oscillation of the beam over a distance d (caused by the resonator oscillation, see fig.4.10) that forms the signal produced by the photodiode. All surfaces that are crossed by the beam have antireflective coating working for wavelengths around 1064 nm. The power arriving at the photodiode is about 2 mW. The last lens the beam passes, lens (d) in fig.3, just before the photodiode, was only added after run 1. This was done to increase the signal at the first mode of oscillation.

The sensitive area of the photodiode, EG&G type C30845E CD2471, is divided into 4 quadrants (figure 4.11), each having an independent output. Each of these outputs goes through an electronic circuit that, next to amplifying the signal and converting it from a current into a voltage signal, forms a fourth order low pass filter with a cut-off frequency of 1.56 kHz. By combining the output of the 4 channels, one can extract information about the beam displacement d.

The channel combination is achieved by means of another electronic circuit, which consists of summing amplifiers. The channels are combined in such a way that the electronic circuit has two output channels, one for the horizontal and one for the vertical displacement of the laser beam. In this way the displacement of the laser beam, due to the vibration of the central load of the resonator, can be measured in 2 orthogonal directions.

Aligning the laser proved to be rather difficult, because the beam has to go and return through the thin tube of the test facility. After this it has to arrive at the center of the photodiode. Centering the laser at the center of the photodiode was done with the aid of a computer program written in Visual Basic that reproduces the laser spot on the quadrants on a computer screen.

4.5 The piezoelectric actuators

Four runs of measurements were done, using a number of different piezoelectric actuators (PZTs), at 293 K (room temperature), 77 K (liquid nitrogen), 64 K, and at 4.2 K (liquid helium). For the 1st run (see section 4.7.1) we placed a piezoelectric
actuator (PZT) (#1) at the side of the aluminum base which supports the transducer. This PZT was disk-shaped with a diameter of about 3 cm, and a thickness of about 4 mm. On top of this PZT we placed a cylinder mass of about 230 gram (see figure 4.12). We used cyano-acrylate to glue the PZT and the mass onto an aluminum cube which was on its turn attached to the base by four brass screws. The capacity of this PZT was 1.35 nF at room temperature (0.7 nF at 4 K). The PZT performed well.

![Figure 4.12: The resonator, supported by the aluminum base. On the right a PZT is visible which has a brass cylinder mass on top of it. Also a thermometer is attached (middle of the base). In the middle of the central load the fused silica substrate with the reflective layer (the mirror) is visible.](image)

For the 2nd run (section 4.7.2) we were more sensitive to the first mode thanks to the extra lens in front of the photodiode. Because of this better signal, we could place the same PZT on the first attenuation-stage, as to avoid the effect of the PZT diminishing the measured mechanical quality factor because of its direct contact. We found the displacement of the resonator surface with the PZT placed at the first stage and exciting with 500 Volt peak to peak ($V_{pp}$) to be more or less the same as the displacement obtained with the PZT down on the supporting mass using 20 $V_{pp}$. So using the PZT at the first stage seemed possible. However, when we cooled down to liquid nitrogen temperature (77 K) we were unable to excite the first mode (at 953 Hz). This was caused by the PZT getting much less efficient at low temperature, in a not very well predictable way. The second mode (at 1553 Hz) was clearly visible however, and we measured (at 77 K) a Q of around 80,000 ± 2000, in agreement with the measurements of Run1 (Q = 77,000 ± 2000). So the position of the PZT (placed either on the first attenuation stage or directly on the base) didn’t have a very large influence on the Q at this frequency and temperature after all.
In order to excite the first mode we placed a new PZT (#2), on the base again, to achieve a larger excitation. This PZT had a capacity at room temperature of 1.46 nF. Some measurements at room temperature were performed. But unfortunately the PZT was damaged during the cool down, and short circuited.

We decided to place 3 new rectangular shaped PZTs (#3a, b and c), with dimensions of 25 mm by 6 mm by 0.6 mm. To attach PZT #3a (capacity 2.65 nF) and #3b (capacity 2.83 nF) we used another type of glue, consisting of two components: 93% epoxy resin stycast 2850gt + 7% catalyst trioxatridecane-diamine, which we put in an oven at 60 degrees Celsius for one hour. For #3c (capacity 2.33 nF) we used the old glue (cyano-acrylate). These 3 PZT’s were placed at the base again at 120 degree angles relative to each other, and again we put masses on top of them, this time of 340 gram (see figure 4.12). We again found that the effectiveness of the PZTs decreases with a decrease in temperature. Lowering the pressure did not influence the effectiveness, as expected.

Because it appeared that the high number of PZTs attached to the base was diminishing the Q (see section 4.7), we decided for Run 3 (section 4.7.3) to remove PZT #3b and #3c, as well as the supporting cubes, and we attached a new PZT (#4) of the same type to the bottom of the supporting 20 kg mass, close to its center, using two component epoxy glue (araldite). It had a capacity of 2.54 nF. We hoped to get a better excitation of the first mode this way (up till now we had been only exciting from the side of the base), exciting from below in a vertical direction (i.e. in the direction of oscillation of the first mode, see section 4.3). With the same glue we attached an aluminum mass of about 150 g to the PZT.

The excitation in this manner however proved to be very poor (about one order of magnitude less than with PZT #3a), probably due to the fact that the PZT plus mass was in this case hanging from the base, which made a poor coupling. We did not use this PZT any more.

We placed a new, smaller PZT (#5) with a capacity of 0.71 nF on top of the resonator, close to the mirror in the center, opposite to PZT #3a. The dimensions were 8 mm by 6 mm by 0.6 mm (it was actually the same type of rectangular PZT as previously used, only now cut of at about one third of its length). We used this PZT for read out only, and it functioned very well: for the first mode it actually had a higher signal to noise ratio (S/N) than the optical readout. All the previously used PZTs were removed, as to not diminish the quality factor again, only #3a was left in place to give the excitation. We used this configuration in Run 3 as well as Run 4. The only difference for Run 4 was that we had to attach PZT #5 at the bottom of the central

Figure 4.13: For Run 4 PZT #5 had to be attached to the bottom, because of the assemble parts on top of the resonator.
load of the resonator instead of on top of it (see figure 4.13). This was done because of the other aluminum parts that we assembled on top of the resonator, which will eventually be necessary for the optical transducer (section 4.7.4). We tried not to excite with to high a voltage because we found a dependence of the Q on the amplitude of oscillation, with higher amplitudes corresponding to lower Qs (see section 4.7.5, figure 4.25). There also appeared to be a dependence of the resonant frequency on the amplitude of oscillation: during the measurements of the decay at 4 K (that took sometimes 20 minutes or more) we saw that with diminishing amplitude of oscillation with time, the resonant frequency was going up slightly. We saw this by comparing the phase of the excitation signal to the phase of oscillation of the resonator. This was another reason to excite with as low a voltage as possible. We excited with voltages ranging from 500 $V_{pp}$ (sometimes necessary to find the resonance frequency, for example at room temperature when the signal-to-noise ratio is poor) down to 0.2 $V_{pp}$ (at 4 K when the signal-to-noise ratio is high).

### 4.6 Calibration of the optical readout

For the first calibration of the optical readout we placed an accelerometer of type PCB 352B19 close to the mirror on the resonator, at an angle of 90° relative to PZT #1, (which we later replaced by PZT #3a, at the same position, see figure 4.14), which at the time of the calibration was placed on the first attenuation stage. We excited the PZT (#1) with a periodic sinusoidal signal with frequency $\nu$ and varying amplitudes, and measured, with a lock-in locked at the same frequency $\nu$ (time-constant 300 ms), the output of the photodiode and accelerometer simultaneously.

![Figure 4.14: Position of the PZTs and the accelerometer (used to calibrate the optical readout) on the resonator.](image)

The vertical displacement of the mirror surface can be calculated from the output signal of the accelerometer using:

$$x = \frac{V}{c \times (2\pi \nu)^2}$$  \hspace{1cm} (4.1)

where $x$ is the displacement in meters, $V$ the output voltage of the accelerometer in Volts, $\nu$ the signal frequency in Hertz, and $c$ is the conversion factor of the
accelerometer which is $4.5 \frac{mV}{g}$ (milliVolt per g, where g is the gravitational constant of 9.8 m/s$^2$). We then have both the displacement and the photodiode output signal at different excitation amplitudes. This way we can make a plot of the photodiode output voltage against the displacement measured by the accelerometer, see figure 4.15. The calibration was done at room temperature and atmospheric pressure, using for the photodiode signal a filter cutting frequencies below 300 Hz and above 3 kHz, as we did for the measurements of the Q.

![Figure 4.15: Amplitude of the output voltage of the vertical channel at the photodiode against the displacement of the resonator surface at a frequency of 906.2 Hz, using a lock-in amplifier with a time constant of 300 ms (for both the photodiode and the accelerometer). The calibration was done just before Run 2. In the used fit $y=ax+b$, the value of $a=(2.9\pm0.9)\times10^{-5}$ V and $b=(2.30\pm0.01)\times10^4$ V/m. The correlation factor is $R=0.99994$.](image)

Just after finishing Run 3 another calibration was performed with the optical readout, PZT #5 and an accelerometer (type PCB 352B10, conversion factor 9.64 mV/g). The accelerometer was attached with a little piece of tape at the same position as before, so at a 90º angle with the excitation PZT, which this time was PZT #3a attached to the base. This calibration was done again at room temperature and atmospheric pressure, with the same filter. See figure 4.16. This calibration however was done using smaller excitations (thus having smaller surface displacements) then during the first calibration, as can be seen from the numbers on the x-axes. This was possible because during the second calibration we were more sensitive to the first mode because of the lens that we added (which was added after the first calibration, see section 4.4).

We see a good agreement between the slopes of the two graphs ($2.30\times10^4$ V/m and $2.16\times10^4$ V/m), considering the fact that we used different accelerometers and that the optical readout was realigned between the two calibrations. Also should be considered that modifications had been made on the resonator between the two calibrations (section 4.3).
Figure 4.16: Amplitude of the output voltage of the vertical channel at the photodiode versus the displacement of the resonator surface at a frequency of 908.18 Hz, as measured just after Run 3. In the used fit $y = a + bx$, the value of $a = (1.6 \pm 0.6) \times 10^{-5}$ V and $b = (2.16 \pm 0.06) \times 10^4$ V/m. The correlation factor is $R = 0.99963$.

### 4.7 Measurements of the resonator mechanical Q

#### 4.7.1 Cryogenic Run 1

As mentioned before, the measurements for Run 1 were done using the optical readout setup without the last lens (lens $d$, see figure 4.9) before the photodiode. This configuration proved not to be optimal for the Q measurements of the first mode, so we added it after Run 1 (see Run 2). In Table 4.1 the Q is listed as measured at Run 1 at different temperatures, down to 4 Kelvin. These are the mean values of the measurements at low pressure ($p = 1 \cdot 10^{-4}$ to $5 \cdot 10^{-6}$ mbar).

<table>
<thead>
<tr>
<th>T (K)</th>
<th>First mode</th>
<th>Second mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency (v)</td>
<td>Quality factor</td>
</tr>
<tr>
<td>293</td>
<td>907.56</td>
<td>9,000 ± 1,000</td>
</tr>
<tr>
<td>77</td>
<td>954.56</td>
<td>20,000 ± 2,000</td>
</tr>
<tr>
<td>64</td>
<td>956.10</td>
<td>28,000 ± 3,000</td>
</tr>
<tr>
<td>4</td>
<td>958.23</td>
<td>**70,000 ± 5,000</td>
</tr>
</tbody>
</table>

* These measurements were not done looking at the decay time as we did for the other measurements; here we determined the Q by measuring the width of the peak (see e.g. figure 4.12).

** Measurements done at a higher pressure of $2 \cdot 10^3$ mbar. This might have resulted in a slightly lower Q.
In figure 4.17 a typical decay graph is shown for a measurement of the Q of the second mode, at 1560 Hz and 4.2 Kelvin.

![Typical decay graph](image)

**Figure 4.17**: Typical decay of the second mode (here at 1560 Hz), with a time constant of $\tau = (520.4 \pm 0.3)$ seconds. The red curve is the exponential fit.

The quality factor was calculated using:

$$Q = \pi v \tau$$  \hspace{1cm} (4.2)

where $v$ is the resonant frequency and $\tau$ the time-constant, which was taken as the decay constant in the exponential fit (as in fig. 11). The data points were taken with a program for decay measurement written in LabView.

Figure 4.18 shows a typical graph of a resonance peak (first mode), at room temperature and a pressure of $6 \times 10^{-6}$ mbar. The fit is a Lorentzian:

$$y = y_0 + \frac{2A}{\pi} \frac{w}{4(x-x_c)^2 + w^2},$$  \hspace{1cm} (4.3)

where $y$ is the amplitude in Volts (V), $y_0$ the base amplitude of the graph (in V), $A$ the area underneath the graph (V·Hz), $w$ the width of the peak at 1/2 of the height (in Hertz), $x$ the frequency (Hz), and $x_c$ the peak frequency (Hz).
Here the quality factor was calculated by dividing the peak frequency by the width $W$ of the peak at $1/\sqrt{2}$ of the height. Obtaining this $W$ can be done using equation (4.3), looking at the values of $y$ at $1/\sqrt{2}$ of the maximum:

$$\frac{y_{max} - y_0}{\sqrt{2}} = \frac{2A}{\pi \cdot w \sqrt{2}} = \frac{2A}{\pi} \cdot \frac{w}{4(x_{12} - x_c)^2 + w^2}$$  \hspace{1cm} (4.4)$$

The roots $x_1$ and $x_2$ of this equation we can then use to calculate the width $W$:

$$W = x_1 - x_2 = w\sqrt{2} - 1 = 0.64 \cdot w$$  \hspace{1cm} (4.5)$$

The expression for the $Q$, as a function of the parameters $w$ and $x_c$ that have been obtained from the Lorentzian fit, now becomes:

$$Q = \frac{\int_0 \infty x_c}{W} \approx \frac{x_c}{0.64 \cdot w} \approx 1.56 \cdot \frac{x_c}{w}$$  \hspace{1cm} (4.6)$$
4.7.2 Cryogenic Run 2

We started the measurements again with PZT #1, this time however we placed it on the first attenuation stage in stead of on the base (see section 4.5). As expected the Q at room temperature turned out to be higher as compared to the measurements with a PZT on the base (made later during Run 2): for the 1st mode we found a Q of 5500 ± 100, for the 2nd mode a Q of 8900 ± 100. At 77 K however the excitation was too weak, so we had to place a PZT on the base again.

We mounted three new PZTs (#3a, b and c) on the aluminum base, at 120 degree angles relative to each other. The results thus obtained are shown in table 2. These values are again calculated from the measurements at low pressure (p=1·10⁻⁴ to 5·10⁻⁶ mbar).

Table 4.2: Quality factor of the first and the second mode, as measured at Run 2.

<table>
<thead>
<tr>
<th>T (K)</th>
<th>First mode</th>
<th></th>
<th>Second mode</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency (v)</td>
<td>Quality factor</td>
<td>Frequency (v)</td>
<td>Quality factor</td>
</tr>
<tr>
<td>293</td>
<td>905.7</td>
<td>4,500 ± 200</td>
<td>1473.8</td>
<td>7,500 ± 500</td>
</tr>
<tr>
<td>77</td>
<td>953.13</td>
<td>15,600 ± 500</td>
<td>1554.4</td>
<td>80,000 ± 2,000</td>
</tr>
<tr>
<td>64</td>
<td>954.50</td>
<td>23,000 ± 500</td>
<td>1556.86</td>
<td>103,000 ± 6,000</td>
</tr>
<tr>
<td>4</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

As can be seen in table 4.2, we didn’t cool down to 4 K, because the measured Q at 77 K and 64 K for the first mode were rather low (around 20% lower than at Run 1, see table 4.1) and because of an unexpected lack of liquid helium. The results of the second mode however were in well agreement with the results of Run 1.

4.7.3 Cryogenic Run 3

As mentioned before, for Run 3 the resonator was slightly modified. At the top side, in the center, a little hole was drilled, where the Fused Silica mirror (diameter 12.7 mm, height 6 mm) was placed (see figure 4.3). This mirror was held by a flange that on its turn is attached to the resonator by six little screws. To relief the pressure induced by the flange and the six screws on the mirror, we placed a little Teflon ring (outer diameter 12 mm, inner diameter 10 mm, thickness 200 µm) on top of the mirror. We use very little torque to turn the screws, because of the pressure increasing even further during cooldown due to the shrinking of the screws. We also replaced the brass screws of the suspension by aluminum ones, cleaning the screw holes very well. This may have positively influenced the Q.

Aligning the laser beam proved difficult, because we often had a too big (beam is partially blocked) or too small (signal is too weak) angle. We managed to obtain a reasonable signal after lifting the last mirror and the last two lenses by a few mm. Apart from the optical readout, which was basically unchanged in respect to the previous run, we also used a PZT (#5) for readout. This PZT was glued on top of the resonator, close to the mirror in the center, see figure 4.14. Like before PZT #3a was
used to excite the resonator. All the other previously used PZTs were removed, as to not diminish the quality factor again.

The mean values of the measured Q, obtained at low pressure (p=1\times10^{-4} to 5\times10^{-6} mbar) and low amplitude of oscillation, are shown in table 4.3.

**Table 4.3: Quality factor of the first and the second mode, as measured at Run3.**

<table>
<thead>
<tr>
<th>T (K)</th>
<th>First mode</th>
<th>Second mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency (v)</td>
<td>Quality factor</td>
</tr>
<tr>
<td>293</td>
<td>905.8</td>
<td>*3,900 ± 200</td>
</tr>
<tr>
<td>77</td>
<td>953.98</td>
<td>*37,000 ± 1,000</td>
</tr>
<tr>
<td>64</td>
<td>954.01</td>
<td>70,000 ± 1,000</td>
</tr>
<tr>
<td>4</td>
<td>956.25</td>
<td>1,260,000 ± 140,000</td>
</tr>
</tbody>
</table>

* These measurements were not done looking at the decay time as we did for the other measurements; here we determined the Q by measuring the width of the peak (see e.g. figure 4.12).
** At 64K we measured a very low Q of 21,000 ± 3,000 for the 2nd mode. This was probably due to exchange gas that was still in the IVC, so we didn’t take these measurements into account any further.

### 4.7.4 Cryogenic Run 4

For Run 4 we mounted a number of aluminum parts (Al5056, the same material as the resonator) on top of the resonator, see figures 4.19 and 4.20 and table 4.4, designed to make the laser beam go into the Fabry-Perot cavity once the transducer is coupled to the bar. This Fabry-Perot cavity is, as was explained in section 3.2, formed between the mirror on the resonator (this is the exit mirror of the cavity) and a second mirror placed on the first aluminum piece (depicted in grey in figures 4.19 and 4.20) on top of the resonator (this is the entrance mirror of the cavity). Both mirrors are held by flanges. Rings of Teflon with a thickness of 100 µm, inner diameter 22 mm and outer diameter 26 mm were used to release the stress, induced by the screws (M4, length 10 mm) that hold the flanges, on the mirrors. One Teflon ring was placed under each mirror, another one on top.

*Figure 4.19: The resonator (yellow) with the aluminum parts, necessary to make the beam fit into the Fabry-Perot cavity, assembled on top of it.*
### Table 4.4: The assembled Al5056 parts as shown in figure 4.20

<table>
<thead>
<tr>
<th>Number</th>
<th>Part</th>
<th>Mass (g)</th>
<th>Color in drawing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Resonator *</td>
<td>5680</td>
<td>yellow</td>
</tr>
<tr>
<td>2</td>
<td>Support for entrance-mirror of transducer-cavity</td>
<td>2420.9</td>
<td>grey</td>
</tr>
<tr>
<td>3</td>
<td>Entrance-mirror of transducer-cavity **</td>
<td>***</td>
<td>blue-grey</td>
</tr>
<tr>
<td>4</td>
<td>Flange for entrance-mirror of transducer-cavity</td>
<td>4.7</td>
<td>green</td>
</tr>
<tr>
<td>5</td>
<td>Support for movement of reflecting mirror</td>
<td>1690.1</td>
<td>orange</td>
</tr>
<tr>
<td>6</td>
<td>External movement device</td>
<td>249.5</td>
<td>turquoise</td>
</tr>
<tr>
<td>7</td>
<td>Reflective mirror</td>
<td>***</td>
<td>purple</td>
</tr>
<tr>
<td>8</td>
<td>Internal movement device</td>
<td>93.1</td>
<td>grey</td>
</tr>
<tr>
<td>9</td>
<td>Flange for external movement device (#6)</td>
<td>154.2</td>
<td>blue</td>
</tr>
<tr>
<td>10</td>
<td>Flange for internal movement device (#8)</td>
<td>75.3</td>
<td>red</td>
</tr>
</tbody>
</table>

* not shown:  
- exit-mirror of transducer-cavity (placed on center of the resonator)  
- flange for exit-mirror of transducer-cavity  
- teflon rings (all mirrors have teflon rings of 100μm thickness on both sides to release stress)

** mirror type: Y1-0537-0 (PO#: 36, SO#: 205323, QTY: 1), height 9mm, diameter 0.5 inch.

*** mass has not been measured, because these are mirrors with a very small mass.

---

**Figure 4.20:** Exploded view of the Al5056 parts and the resonator.
Chapter 4: Mechanical Quality Factor of the Resonant Transducer

For Run 4 we couldn’t use the optical readout, because the beam was blocked by the new aluminum parts, so we used only PZT #5. This time we had to glue it to the bottom side of the resonator (see figure 4.13), because of the aluminum parts that were now on top of the resonator. The wires to the PZT #5 went through the hole of about 2 cm in diameter that has been made in the supporting base. We made sure that the wires did not touch the base, as to not diminish the Q. A picture of the resonator with the Al5056 parts assembled on top of it in the test facility is displayed in figure 4.21.

![Figure 4.21: Picture of the resonator with all the Al5056 parts on top, placed in the test facility.](image)

In Run 4 we wanted to know what the effect was of these new parts which were assembled on top of the resonator, so we conducted a full run down to 4 K. The results are shown in table 4.5. These values are again calculated from the measurements at low pressure (p=1·10⁻⁴ to 5·10⁻⁶ mbar) and low amplitude of oscillation.

<table>
<thead>
<tr>
<th>T (K)</th>
<th>First mode</th>
<th>Second mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency (v)</td>
<td>Quality factor</td>
</tr>
<tr>
<td>293</td>
<td>908.2</td>
<td>3,400 ± 100</td>
</tr>
<tr>
<td>77</td>
<td>955.1</td>
<td>37,000 ± 1,000</td>
</tr>
<tr>
<td>64</td>
<td>957.16</td>
<td>56,000 ± 3,000</td>
</tr>
<tr>
<td>4</td>
<td>959.26</td>
<td>960,000 ± 60,000</td>
</tr>
</tbody>
</table>
The combination of the resonant transducer with the aluminum parts assembled on it, as it will be positioned on the low temperature bar is shown in figure 4.22.

![Image](4841438423361x77539 to 16161480923361x106654)

**Figure 4.22**: view of the bar with attached to it (at the bar end face) the resonant transducer with the assembled aluminum parts. On the brown rectangular bench on the top middle of the bar, some optical components (e.g. lenses) are placed. It is here that the laser beam, via an optical fiber, enters the cryostat; it is then sent by these optical components to the yellow ‘fork’ at the end of the bar, which sends it to the resonant transducer.

### 4.7.5 Overview of the mechanical Q measurements

To make for easy comparison, the results of the quality factor measurements of the 1\textsuperscript{st} mode of all four runs, already given separately in the four subsections above, are put together in table 4.6. A plot of these quality factor values against the temperature is given in figure 4.23.

**Table 4.6: Quality factor of the 1\textsuperscript{st} mode at four different runs.**

<table>
<thead>
<tr>
<th>T (K)</th>
<th>Q Run 1</th>
<th>Q Run 2</th>
<th>Q Run 3</th>
<th>Q Run 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>293</td>
<td>*9,000 ± 1,000</td>
<td>4,500 ± 200</td>
<td>*3,900 ± 200</td>
<td>3,400 ± 100</td>
</tr>
<tr>
<td>77</td>
<td>20,000 ± 2,000</td>
<td>15,600 ± 500</td>
<td>*37,000 ± 1,000</td>
<td>37,000 ± 1,000</td>
</tr>
<tr>
<td>64</td>
<td>28,000 ± 3,000</td>
<td>23,000 ± 500</td>
<td>70,000 ± 1,000</td>
<td>56,000 ± 3,000</td>
</tr>
<tr>
<td>4</td>
<td>**70,000 ± 5,000</td>
<td>--</td>
<td>1,260,000 ± 140,000</td>
<td>960,000 ± 60,000</td>
</tr>
</tbody>
</table>

* Measurement of the width of the peak.
** Measurements done at a higher pressure of 2·10\textsuperscript{-3} mbar. This might have resulted in a slightly lower Q.
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The results of the quality factor measurements at the second mode of all four runs together (also already given in the previous subsections) are shown in table 4.7. An overview of the Q against the temperature T at all four runs is plotted for the 2\textsuperscript{nd} mode in figure 4.24.

\textbf{Figure 4.23: Quality factor against temperature for the 1\textsuperscript{st} mode at four different runs.}

\textbf{Table 4.7: Quality factor of the 2\textsuperscript{nd} mode at four different runs.}

<table>
<thead>
<tr>
<th>T (K)</th>
<th>Q run1</th>
<th>Q run2</th>
<th>Q run3</th>
<th>Q run4</th>
</tr>
</thead>
<tbody>
<tr>
<td>293</td>
<td>11,700 ± 700</td>
<td>7,500 ± 500</td>
<td>3,700 ± 100</td>
<td>--</td>
</tr>
<tr>
<td>77</td>
<td>77,000 ± 2,000</td>
<td>80,000 ± 2,000</td>
<td>54,600 ± 400</td>
<td>48,000 ± 4,000</td>
</tr>
<tr>
<td>64</td>
<td>105,000 ± 4,000</td>
<td>103,000 ± 6,000</td>
<td>--</td>
<td>86,000 ± 6,000</td>
</tr>
<tr>
<td>4</td>
<td>5.3 \cdot 10^6 ± 20,000</td>
<td>--</td>
<td>560,000 ± 30,000</td>
<td>1.15 \cdot 10^6 ± 70,000</td>
</tr>
</tbody>
</table>

* Measurement of the width of the peak.
To show the dependence that clearly exists (as was mentioned previously in section 4.5) of the mechanical Q on the amplitude of oscillation, in figure 4.25 the measurements of Run 3 at 4 K of the 1st mode are shown. The x-coordinates of these eight measurements correspond to the amplitude of the signal in mV as was obtained by PZT #5. This corresponds to the amplitude of oscillation of the resonator surface. The values in mV are taken at the point were we started the fit of the data (as the amplitude of oscillation decreases with time, see for example figure 4.17).

We see that the higher the signal obtained by the PZT (and thus the higher the displacement of the resonator surface, i.e. the amplitude of oscillation), the lower the mechanical quality factor is. The difference in this case can be more than a factor of 2.
Figure 4.25: Graph of the mechanical $Q$ as a function of the amplitude of the signal obtained by PZT #5 that is a measure of the amplitude of oscillation of the resonator surface. These are the values at the beginning of the fit of the data. Measurements are all done during Run 3 at 4 K, 1$^{st}$ mode.

4.7.6 Second resonance mode: a doublet

As explained before, the second mode of oscillation is actually a doublet. This means that there are two orthogonal oscillations at slightly different frequencies. This results in two peaks when the oscillation amplitude is measured as a function of frequency around resonance. In figure 4.26a, b and c graphs are given of the resonance peaks at 77 K, read out with the photodiode, while exciting with PZT #3a, b, and c respectively. Because we can measure the movement only in one of two fixed directions at a time (either with the horizontal channel or with the vertical channel of the photodiode) the peaks are different for all three measurements. Clearly the position of the used PZT (together with the position of the screws that fix the resonator to the base and that transmit the vibration) determines the orientation of the two orthogonal oscillations, and thus their component in the direction of the measurement channel (see figure 4.27 for a schematic drawing of the setup).

The measurements here were done with the vertical channel. As a result the two peaks, which resemble the two orthogonal oscillations with slightly different resonant frequencies, both vary in height depending on which PZT is used. The first peak of each graph (at about 1554.17 Hz) is the oscillation orientated in the direction of the PZT, the second peak represents its orthogonal component.
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Figure 4.26a: Second mode resonance peaks excited with PZT #3a, measured with the vertical channel.

Figure 4.26b: Second mode resonance peaks excited with PZT #3b, measured with the vertical channel.
### Chapter 4: Mechanical Quality Factor of the Resonant Transducer

#### Figure 4.26c: Second mode resonance peaks excited with PZT #3c, measured with the vertical channel.

<table>
<thead>
<tr>
<th>Peak</th>
<th>Centerfreq. (Hz)</th>
<th>Width (Hz)</th>
<th>Height (Vrms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1554.163 +/- 0.003</td>
<td>0.092 +/- 0.008</td>
<td>0.161</td>
</tr>
<tr>
<td>2</td>
<td>1554.415 +/- 0.014</td>
<td>0.096 +/- 0.005</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Yoffset = 0 (Vrms)

#### Figure 4.27: Orientation of the two orthogonal oscillations (shown for PZT #3a with the red lines) as a result of the position of the PZTs, relative to the two channels of measurement (Vertical and Horizontal).
Chapter 5

Conclusions

As a part of the development of an optical readout for the gravitational wave bar detector AURIGA, an Al5056 resonator was developed. The main work for this thesis concerned the testing of the mechanical Q of this resonator at low pressure and different temperatures down to 4 K. Knowing the behaviour of the Q of the resonator will be useful for the test at cryogenic temperatures of the bar with the optical transducer, planned for the near future. In the course of the experimental work for this thesis four runs have been done, with different configurations of the resonator and readout. Measurements of the Q were done at two different modes of resonance, the first being at around 958 Hz and the second at around 1560 Hz (both at 4 K).

For Run 1 at 4 K we found a Q of $(7.0 \pm 0.5) \times 10^4$ for the 1$^{\text{st}}$ mode and a Q of $(5.30 \pm 0.02) \times 10^6$ for the 2$^{\text{nd}}$ mode. Since the Q of the first mode, which is of interest to us for the optical transducer, turned out to be rather low, we decided to change the optical readout configuration for Run 2, in order to increase the signal of the 1$^{\text{st}}$ mode: in fact we suspected that the low Q was due to additive losses that appear at high level of vibrations. We also tried placing the PZT, used to excite the modes, on the first attenuation stage instead of on the supporting mass, as to avoid the Q being lowered due to losses to the attached PZT and the mass on top of it. We see that doing so increased the quality factor.

Also we noticed, looking at the results of the 2$^{\text{nd}}$ mode at Run 1 at 4 K, that the excitation was too high because we saw the slope of the logarithm of the decay (which was expected to be constant) getting less with time. There exists a clear dependence of the Q on the amplitude of oscillation: the lower the amplitude, the higher the Q. The results of later runs confirm this.

We thus tried exciting with smaller amplitude at Run 2, as to have a higher Q. We see however that the Q measured at the 2$^{\text{nd}}$ mode did not change, except for the room temperature measurement. For the 1$^{\text{st}}$ mode the Q was roughly 25% less than that measured during Run 1. Probably the lower Q can be explained for low temperature (77 K) by the fact that we had three PZTs (with masses on top of them) attached during Run 2 instead of one at Run 1. We didn’t cool down to 4 K because of an unexpected shortage of helium.
Before Run 3 some modifications were made on the resonator as to make it compatible for operation on a cryogenic bar. A little hole was drilled in the middle of the central load wherein a mirror was placed. All but one PZT were removed. The Q of the 1\textsuperscript{st} mode turned out to be \((1.26 \pm 0.14) \cdot 10^6\) which was much higher than measured in the previous runs. It is not entirely clear where this drastic increase of the Q comes from, but the removal of 2 of the 3 PZTs and masses as well as replacing the brass screws of the suspension by aluminum ones contributed undoubtedly.

After Run 3 some aluminum parts were assembled on top of the resonator, which will make the laser beam arrive in the right way at the transducer cavity once the resonator is fixed to the low temperature bar. Because of this, in Run 4 the Q of the 1\textsuperscript{st} mode turned out to be about 25\% lower compared to Run 3, namely \((0.96 \pm 0.06) \cdot 10^6\). The effect of the extra components was probably the reason for the lower Q. The diminishing of the Q was expected, and the Q of almost one million after assembling all the parts is encouraging for the future. It shows that the resonator with the assembled parts can be used in the optical readout chain on the cryogenic bar.

The optical readout on top of the test facility that we used for the aforementioned mechanical Q measurements functioned very well for the measurements of the 2\textsuperscript{nd} mode, which concerns movements of tilting of the central load of the resonant transducer. For the 1\textsuperscript{st} mode, concerning movement perpendicular to the resonator surface, the readout demonstrated some difficulties, which were however not due to intrinsic limits of the optical readout itself but to the geometric boundaries of the test facility.

Therefore aligning the optical readout of the test facility took a long time, typically two days. This was due to the fact that the beam had to go through a 2 m long pipe, under exactly the right angle of 0.2 degrees. If the angle was too small, the signal was too small; if the angle was too big the laser beam would not pass through the window which closes off the IVC. If the window could in the future be made larger, then the angle can be larger too and the signal to noise ratio of the readout thus higher. Also the aligning would be much easier and take in the order of two hours rather than two days. Furthermore, Run 3 and Run 4 show that a small PZT can also be used for readout, but that has the disadvantage of not being a non-touching readout.

In the near future the optical transducer will be fully tested at cryogenic temperatures on a similar bar as AURIGA. A positive outcome of this test will open the possibility to use the optical readout (in an adapted configuration) on a new generation of resonant mass gravitational wave detectors, the dual detector. The feasibility of such a detector is presently under study in the AURIGA group. Both the bandwidth and the sensitivity of a dual detector could be higher than the sensitivity of the present day resonant antennas, and therefore a dual detector could be a good alternative for the laser interferometers, being sensitive at other frequencies.

A small part of the work for this thesis was done at the Kamerlingh Onnes Laboratory at Leiden University, The Netherlands. It consisted of the measurement of the mechanical Q at different temperatures down to 4 K of an Al5056 resonator which is the second stage in an inductive transducer now under development and to be used for the spherical gravitational wave detector MiniGRAIL.

Two runs were done, one before and one after depositing a Niobium thin layer of 500 nm, to determine the effect on the mechanical Q of the sputtering of this layer. We see...
that the mechanical Q of the transducer mode (the mode of interest to us) was about 25 % lower after the deposition of the Nb layer. However, the mechanical Q remained reasonably high at $(1.00 \pm 0.05) \cdot 10^6$. This means that the Al5056 resonator with Nb layer on top can be used as a second mechanical stage in the inductive transducer. Tests of a prototype inductive transducer, existing of the Al5056 resonator together with a superconducting coil as a pick-up mechanism, have already been done and provide useful data for further developments of an inductive transducer that could be used for MiniGRAIL in the future.
Summary

For the gravitational wave bar detector AURIGA an optical readout is being developed. This optical readout makes use of an optical resonance cavity (a Fabry-Perot cavity), which is formed between the bar and an Al5056 resonant transducer coupled to the bar. When a gravitational wave hits the bar, it induces a bar vibration; this vibration is mechanically amplified by the resonant transducer. The time varying relative displacement between the bar and the transducer, and thus a time varying length of the optical cavity (called transducer cavity) means a time variance of its optical resonance frequency. Via a feedback loop, making use of the FM-sidebands technique, the laser is frequency-locked to the transducer cavity, which is in this way kept at resonance. The laser frequency is then compared with the resonance frequency of a reference cavity, whose length and thus resonance frequency is actively kept constant; in this way a possible gravitational wave signal can be extracted.

An important aspect in the sensitivity of resonant gravitational wave detectors is the thermal noise, which must be as low as possible (other noise sources are for example back-action noise, electronic noise, etc.). The thermal noise depends linearly on T/Q, where T is the thermodynamic temperature and Q the mechanical quality factor. In order to get this noise down, the temperature must be as low as possible, and the mechanical Q (which is a factor of 2 to 3 higher at low temperatures) as high as possible. Therefore the detectors are cooled to (ultra)cryogenic temperatures.

The mechanical Q of the Al5056 resonant transducer was tested in the cryogenic test facility of the AURIGA laboratory at the Legnaro National Laboratories (INFN, Italy). Four cryogenic runs were done to test the mechanical Q of two modes of oscillation at different temperatures down to 4 K (1\(^{st}\) mode around 958 Hz at 4 K, 2\(^{nd}\) mode around 1559 Hz at 4 K). Between the runs modifications were made on the readout setup and the transducer itself. For the last run a number of aluminium parts were assembled on top of the resonator, which will be needed to direct the laser beam to the transducer cavity once the resonant transducer will be coupled to the low temperature bar. An optical readout setup (making use of a quadrant photodiode) was used, which performed very well for the measurements at the 2\(^{nd}\) mode, but proved to function less well for the 1\(^{st}\) mode. This however was mainly due to limitations of the test facility and not to intrinsic properties of the optical readout. For the last two runs also a PZT was used for readout. To induce the oscillation of the resonant transducer, a number of PZTs with masses on top of them were tried, placed at different positions near the resonant transducer.
Summary

The mechanical Q at 4 K of the 1st mode, which is the mode of interest to us, proved rather low in the 1st Run: $(7.0 \pm 0.5) \cdot 10^4$. For Run 2 we changed the configuration of the readout, but no measurements could be done at 4 K due to an unexpected lack of helium. However, for Run 3, before which changes on the resonant transducer itself had been made, the mechanical Q was measured to be $(1.26 \pm 0.14) \cdot 10^6$. At Run 4 some extra Al5056 parts were mounted on top of the resonator, which caused the Q to drop to $(0.96 \pm 0.06) \cdot 10^6$.

A minor part of the work for this thesis was done at the Kamerlingh Onnes Laboratory at Leiden University, The Netherlands. It regarded the development and mechanical quality factor measurements of a small Al5056 resonator with an oscillating top plate of 1.5 g. This resonator forms the second mechanical amplification stage of and inductive transducer now being developed for the spherical gravitational wave antenna MiniGRAIL. The mechanical Q at two modes of oscillation (1st mode around 3267 Hz at 4 K, 2nd mode around 6271 at 4 K) was measured before and after the deposition of a thin Niobium layer of 500 nm on the top plate, in order to determine the effect of this deposition on the mechanical Q. Again, the 1st mode is the mode of interest to us and concerns motion in a direction perpendicular to the resonator top plate surface. Before depositing the Nb layer we measured for this 1st mode a Q of $(1.35 \pm 0.05) \cdot 10^6$; after depositing, the Q turned out to be about 25% less, having a value of $(1.00 \pm 0.05) \cdot 10^6$. 
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