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Optical metrology for massive detectors of gravitational waves

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Abstract

The high level reached in the stability of laser sources and in the quality of optical components makes interferometric metrology appealing to those involved in the search for detection of gravitational waves (GWs). In this paper we present a readout for massive detectors of GWs, based on laser interferometry with high finesse Fabry–Pérot cavities, and describe the frequency stability of the laser source. The achievable sensitivity at the quantum limit level inherent to this technique requires a careful design, in order to reduce other sources of extra noise. In particular, we focus on the local effects of thermal and radiation pressure fluctuations and present an optical configuration that can reduce these effects below the quantum limit level.

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Keywords: Fabry–Pérot cavity; Gravitational wave detectors; Thermal noise; Radiation pressure

1. Introduction

The search for gravitational waves (GWs) is one of the most challenging tasks for experimental physics and has a major role in stimulating progresses in optical techniques aimed at interferometric detection of extremely small displacements. The existence of GWs was predicted by Einstein as a consequence of his general theory of relativity [1], according to which an accelerating mass would produce a ripple of the spacetime, which propagates at the speed of light as a transverse wave. The passage of a GW can be detected by the effect produced on free-falling test masses, whose relative distances change as the spacetime distortion passes by. The experimental search for GWs began in 1960 and was based on massive acoustic detectors [2]. Recently, long baseline interferometers began to operate as well [3]. However, up to now there is no direct evidence of GWs, even though measurements made on binary stellar systems are in excellent agreement with the predicted loss of energy by emission of GWs [4].

The massive detectors currently operating are cylinders made of aluminum alloy, with a mass of few tons, isolated from mechanical and seismic noise and cooled to cryogenic temperatures (around or below 1 K) for reducing the thermal noise due to Brownian motion. The passage of a GW excites the first longitudinal mode of the cylinder and the vibration of the bar is converted into an electromagnetic signal by a transducer. The detectors of this kind are resonant, as the frequency response peaks around the frequency of the mechanical mode (i.e., around ~1 kHz).

Cryogenic bar detectors operate equipped with a capacitive or inductive transducer, along with SQUID (superconducting quantum device) electronic amplifiers, as readout system for extraction of the GW signal. An alternative scheme, based on interferometric technique, was later proposed and investigated by Richard [5]. The progress made in the last years in the field of laser stabilization and performances of optical components made interferometric techniques more promising for extending the sensitivity of the detectors down to the

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quantum limit level and could result in a major advance for massive GW detectors.

A prototype of the optical readout has been successfully implemented and operated at room temperature in the framework of the AURIGA collaboration, and in the near future a new version will be tested at low temperatures. The scheme of the readout and its performance at room temperature are described in Section 2. In view of the operation at low temperature, and therefore at a better attainable sensitivity, the laser system requires a higher frequency stability than at room temperature and in Section 3 we present and discuss the performance of the laser system conceived for the readout on a cryogenic detector bar.

In recent years new configurations of massive detectors have been proposed, which would work in a range of frequency between 1 and 5 kHz, complementary to that of the long arm interferometers. An interesting scheme is based on two nested masses, with spherical or cylindrical symmetry [6,7]. This scheme is inherently nonresonant, overcoming the restriction on the useful bandwidth typical of the resonant bar detectors. With such a solution the wideband noise of the readout becomes more important and a crucial issue for the transducer is that it must read a large area of the detector surface, in order to average over local effects of thermal and back-action fluctuations. We present in Section 4 an analysis of local effects as sources of noise and then describe, in Section 5, a new configuration of Fabry–Pérot cavity which allows to reduce them while keeping the sensitivity of a high finesse cavity.

2. The optical readout

The basic idea for the optical readout, Fig. 1, is to use a high-finesse Fabry–Pérot cavity made by two mirrors, one fixed to one end of the cylinder and the other mounted on

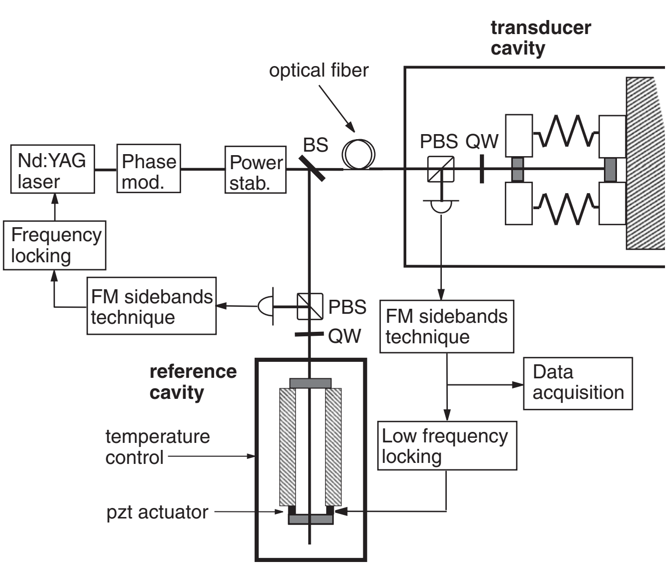

Fig. 1. Scheme of the optical readout. BS: beam splitter; PBS: polarizing beam splitter; QW: quarter-wave retarding plate.

the resonant part of the transducer. The length of the cavity is then compared with that of a stable reference cavity (RC) by means of a resonant laser [8].

The bar of the detector is a cylinder of Al5056, 3 m long, 0.6 m in diameter and with a mass of about 2300 kg. The bar is enclosed in a vacuum chamber, kept at room temperature, and isolated from the floor vibration by several stages of mechanical filters. The first longitudinal mode of the bar resonates at 875 Hz, with a mechanical quality factor Q of 1.8×10^5, as estimated by a decay time measurement. The vibration of the bar is mechanically amplified by a second oscillator resonantly coupled to the bar. A Fabry–Pérot cavity is formed by one mirror fixed to one end of the bar and the other fixed to the coupled oscillator, called transducer mass. Thus, the mechanical vibrations of the bar, possibly due to a GW, are amplified and transformed into length changes of the optical cavity, hereafter transducer cavity (TC). For the transducer mass the mechanical Q has been estimated to be 6600 from thermal noise measurements.

A Nd:YAG laser, emitting 50 mW at 1064 nm, is frequency stabilized with respect to the TC, according to a frequency modulation technique. A thermally stabilized electro-optic modulator (EOM) working at 13.3 MHz modulates the phase of the laser beam. Then, part of the beam (about 2 mW) is sent into the vacuum chamber, through a polarization-maintaining single-mode optical fiber, and directed to the TC by means of tilting mirrors and coupling lenses. The light reflected by the TC is diverted by an optical circulator onto a photodetector. The TC is 6 mm long, it is made by a plane and a spheric (curvature radius 1 m) mirror and its finesse is 28 000. The ac component of the photodetector signal is amplified and demodulated at 13.3 MHz, according to the Pound–Drever–Hall (PDH) scheme [9]. The remaining part of the beam is sent to a stable RC, placed on the optical table, and the light reflected by RC is detected and demodulated as well. The RC is made of two mirrors separated by a 10-cm-long Invar spacer and a 1-cm-long PZT actuator, to allow the tuning of the cavity. The RC finesse is 44 000.

The PDH signal coming from the RC is used as discriminator for frequency locking of the laser. In this way the laser is locked to a resonance of RC by a servo loop with unity gain frequency of 30 kHz and a gain of 130 dB around 1 kHz. The frequency stability of the locked laser is less than $0.1\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ around 1 kHz. After locking the laser the PDH signal from the TC is used as discriminator for a second servo loop which acts on the PZT of the RC and keeps the laser frequency tuned to a resonance of the TC. This second servo loop has a bandwidth of 10 Hz, thus the two cavities can be considered as independent in the frequency range of interest, i.e., around the bar resonance.

The PDH signal from TC carries the information about the relative position of the TC mirrors. It is acquired and analyzed by the software currently used for the ultracryogenic AURIGA detector. The conversion from voltage into