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Cryogenic Q-factor measurement of optical substrate materials

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Abstract. Upcoming generations of interferometric gravitational wave detectors are likely to be operated at cryogenic temperatures because one of the sensitivity limiting factors of the present generation is the thermal noise of optical components (e.g. end mirrors, cavity couplers, beam splitters). The main contributions to this noise are due to the substrate, the optical coating, and the suspension. The thermal noise can be reduced by cooling to cryogenic temperatures. In addition the overall mechanical quality factor should preferable increase at low temperatures. The experimental details of a new cryogenic apparatus for investigations of the temperature dependency of the Q-factor of several substrate materials in the range of 5 to 300 K are presented. To perform a ring down recording an electrostatic mode excitation of the samples and an interferometric read-out of the amplitude of the vibrations was used.

1. Introduction

Future generations of interferometric gravitational wave detectors - currently in design state - will presumable benefit from cryogenic techniques to reduce the thermal noise of optical components. Currently a number of different substrate materials as sapphire, calcium fluoride, and silicon in combination with dielectric coatings and nano-structured surfaces are considered [1,2]. To minimize thermal noise the goal is to find a combination that maximizes the mechanical quality factor Q at some realistic cryogenic temperature [3].

The mechanical Q-factor is a commonly used criterion for the material selection of crucial detector parts. This parameter is experimentally available at the resonant frequencies of the test bodies typically occurring in the 10s kHz range in case of mirror-sized components. Then thermal noise of gravitational wave detectors at detection frequencies can be inferred [4] by assuming frequency independent losses. Nevertheless it must be taken into account that the Q-factor is generally dependent on temperature and amplitude. In this contribution first results of the dependence on temperature of certain samples after commissioning a new cryogenic Q-measurement apparatus are shown. Further detailed investigations are planned. The measurements are performed with oscillations in the nm range.

Current research studies the applicability of beam splitters and cavity couplers based on reflective diffraction gratings. All-reflective interferometers were demonstrated recently [5]. The combination of both, cryogenic temperatures and diffractive optics is a sophisticated technical challenge. The final goal is to demonstrate a cryogenic cavity composed of diffractive couplers and end mirrors. Using such cavities in gravitational wave detectors the sensitivity will be enhanced enormously and therefore the detection of gravitational waves will be improved greatly.

2. Experimental Setup

Figure 1 shows the schematic view of our new cryogenic apparatus allowing the measurement of the temperature dependence of the Q-factor in the range of 5 K up to 300 K. It provides a He vapour-cooled probe chamber housing the pendulum suspended test body. For lowering the heat entry into the probe volume it is surrounded by two heat-radiation shields one connected to the liquid helium tank and one to the liquid nitrogen tank. All shields and vacuum chambers are equipped with an optical window for the interferometric vibration read-out. For maintenance and test sample exchange all shields can be removed easily. The probe volume is placed above the cryogenic tanks. This unique design enables the operator to build up easily different suspension systems at the cold plate to investigate the influence of the suspension system (e.g. wire length, material, diameter) on the measured Q-factor. Also the excitation and read-out system can be fully adjusted before closing the cryostat.

The probe volume is cooled by the boil-off gas from the liquid helium tank using a heat-exchanger at the bottom of the experimental platform. The helium gas flow is adjustable to control the cooling power. This technique provides low mechanical disturbances which is an important issue due to the small vibration amplitudes to be measured. Another advantage of this design is that the boil-off rate of the helium tank is independent from the probe temperature.

The test sample is hung-in as a pendulum inside of the probe volume using tungsten wire with a diameter of 50 µm. This provides a low loss suspension and an excellent decoupling from outer mechanical disturbances.

To change the sample's temperature helium gas with a residual pressure of about 100 Pa is applied to the probe volume. The probe volume temperature is controlled by a LakeShore 340 temperature controller [6]. For thermometry a second test sample (identical in shape and material) is placed in the probe volume. A silicon diode is attached to the second test body to measure its temperature. After thermal equilibrium is reached the probe volume is evacuated. With a vacuum better than 10^{-2} Pa a temperature drift of lower than 200 mK per hour was achieved.

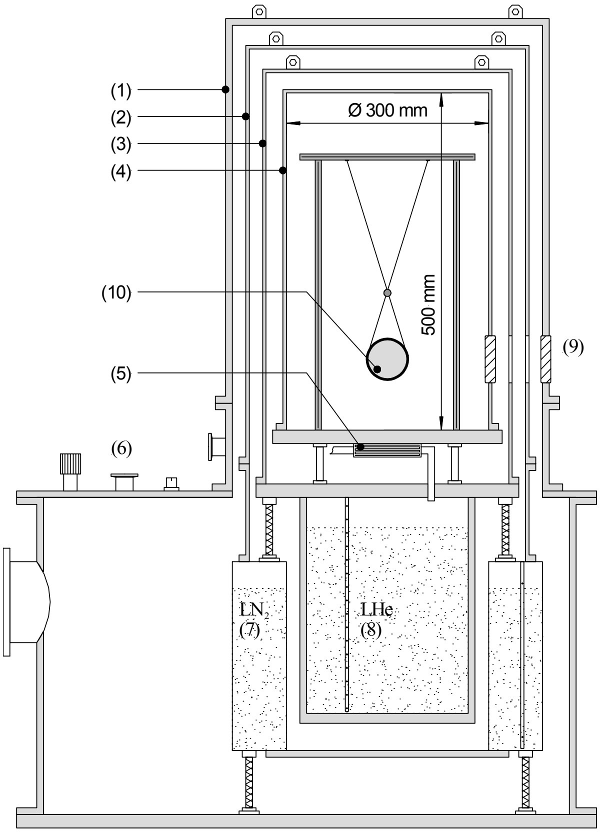

Figure 1: Schematic view of the cryostat providing 4.2 K to 300 K at the probe volume. The probe volume (4) with a diameter of 300 mm and a height of 500 mm is cooled by a heat exchanger (5). It is surrounded by a 4.2K-shield (3) and a 77K-shield (2). Optical windows (9) in all shields allow the use of optical interferometers for read-out. The LHe- (8) and LN$_2$-tanks (7) are placed below the experimental platform. Feedthroughs (6) for sensors and the contact gas are available. The test sample (10) is suspended by a tungsten wire loop as a pendulum.

3. Results

Figure 2 shows the operation parameters during a full cool-down cycle. When the test sample is installed the insulation vacuum is pumped by a turbomolecular pump over 48 hours. Afterwards, the LN_2-tank is filled and then the LHe-tank is cooled to 77 K. This lasts at least 24 hours. The cryostat is then filled with LHe and Q-measurements can be done. With a boil-off rate of about 1.4 l/h LHe the measurement cycle is about 34 hours.

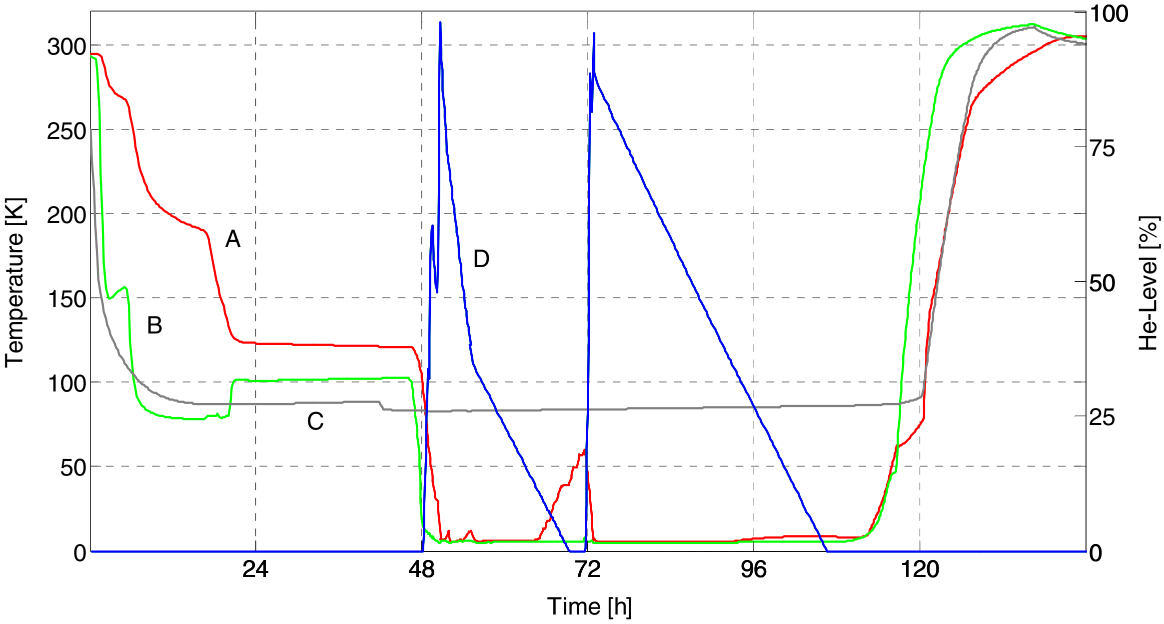

Figure 2: Operating parameters during a full cool-down cycle. A – probe temperature, B – He tank temperature, C – N_2 tank temperature, D – LHe level. The LHe boil-off rate is about 1.4 l/h LHe. Measurements at the lowest temperature are available during approximately 34 hours. The over-all cycle is about 7 days for one test sample.

When the test body has reached the desired temperature the probe volume will be evacuated. For a non-contact excitation of the test body an electrostatic exciter is used. A meander shaped capacitor is connected to a high-voltage source which is fed by an adjustable frequency generator. By applying a high AC voltage (up to 1600 volts) with a frequency close to the test body's eigenfrequency the test sample can be excited to vibrations with amplitudes in the nanometer range. This vibration is measured optically by a commercial Michelson-like interferometer device [7]. This interferometer allows vibration detection with an amplitude sensitivity of 0.1 nm within a frequency range from 0.1 to 500 kHz.

When the amplitude reaches an observable value the exciter is switched off and the free decaying vibration is recorded (see Fig. 3a). From the ring-down time τ the Q-factor can be calculated by

$$Q = \pi \cdot f_0 \cdot \tau ,$$

with the eigenfrequency f_0 of the test body.

To test and characterize the new cryogenic setup crystalline quartz was used as test material as it is well-known from the last decades [8-14] and some literature is available for comparison. Figure 3a gives two ring-down measurements at different temperatures of a crystalline quartz sample. By cooling from 300 K to 6.7 K the Q-factor increases from 3.0×10^{6} to 3.3×10^{7}. Please note that the thermal noise is not measured directly. Here the dependence of the Q-factor on temperature was studied at amplitudes in the nm range and at the eigenfrequencies of the test bodies. Subsequently, the thermal noise can be estimated, e. g. using Levin's approach [15]. To determine the Q-factor with an accuracy of about 5% (accuracy of the fit algorithm) in our setup it is required to record the ring-down process to at least 1 τ according to the system noise. A longer recording time would be helpful in order to estimate amplitude-dependent effects but dramatically reduce the number of measurements possible within one cool-down cycle. According to our experience a Q-factor dependence on the excited amplitude could not be observed within the range of 0.1 nm to 1 μm.

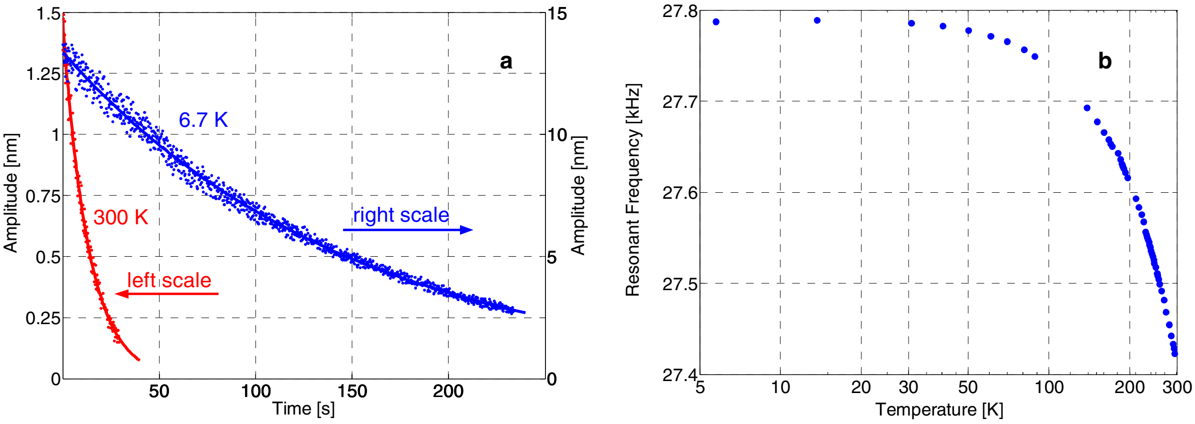

Figure 3: **a)** Examples of ring-down measurements at 300 K and 6.7 K. Substrate material: Crystalline Quartz, ∅ 76 mm, d = 24 mm, resonant frequency: 70.8 kHz, tungsten wire (∅ 50 μm) suspension. The ring-down times correspond to a Q-factor of $(3.0\pm0.1)\times10^{6}$ at 300 K and $(3.3\pm0.3)\times10^{7}$ at 6.7 K. **b)** Shift of the resonant frequency of a test sample (∅ 76 mm × 24 mm, crystalline quartz, tungsten wire suspension loop). The fundamental drum mode was used for this measurement. The monotone behavior can be used to estimate the probe temperature.

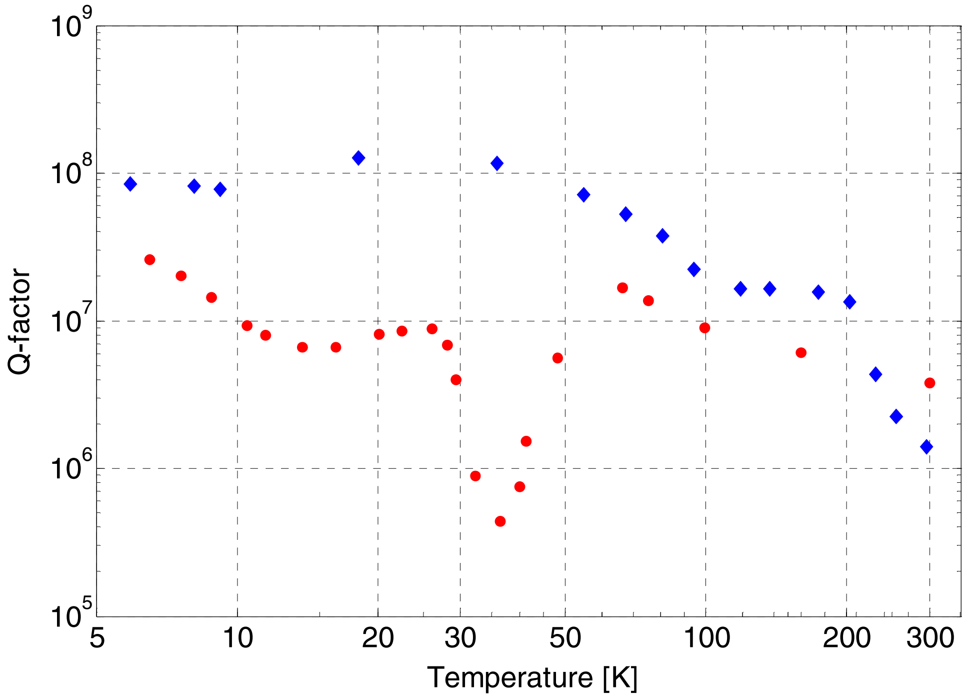

Figure 4: Measurement of the Q-factor of a crystalline quartz sample • and a silicon sample ♦ (both ∅ 76 mm × 24 mm, tungsten wire loop suspension) vs. temperature.

In addition the shift of the eigenfrequency with decreasing temperature of the test substrate was investigated (see fig. 3b). The monotone behavior observed can be alternatively used to estimate the probe temperature above approximately 40 K due to the vanishing slope at low temperatures. Especially the temperature stability of the sample can be confirmed by observing its eigenfrequency. Being able to detect a frequency shift of less than 10 mHz it is possible to sense a temperature variation of less than 10 mK assuming a slope of 1 Hz/K which was observed near 50 K.

Besides crystalline quartz a silicon sample was measured. Silicon is a promising candidate as substrate material for gravitational wave detectors due to its low internal loss. Figure 4 shows the dependence of the Q-factor of these two different materials on the temperature. At 37 K the Q-factor of crystalline quartz decreases due to impurities in the crystal [8-10]. A second decline at 15 K is caused by interactions of thermal phonons with the sound waves having a wavelength in the order of the phonons' mean free paths [11-14]. In contrast, the silicon sample shows an increasing Q-factor with decreasing temperature down to 18 K. Below the Q-factor decreases slightly. This preliminary measurement gives a top Q-factor of 1.2×10^{8} at (18 ± 0.5) K for a quite large Si[100] test mass (∅ 76 mm × 24 mm). Using this material the prospect of new cryogenic interferometer parts (end mirrors, beam splitters) is founded.

To give a rough estimate of the improvement of cooling optical components a numerical calculation was done based on the experimental results. This has been performed according to Levin's direct approach [15], using the FEA software ANSYS. A mirror substrate with GEO600-like geometry and a Q-factor of 1×10^{8} at 10 K was assumed. Figure 5 gives the results at 300 K and 10 K in comparison to the current overall noise of GEO600. Thermal noise can be reduced by at least one order of magnitude compared to the room temperature configuration.

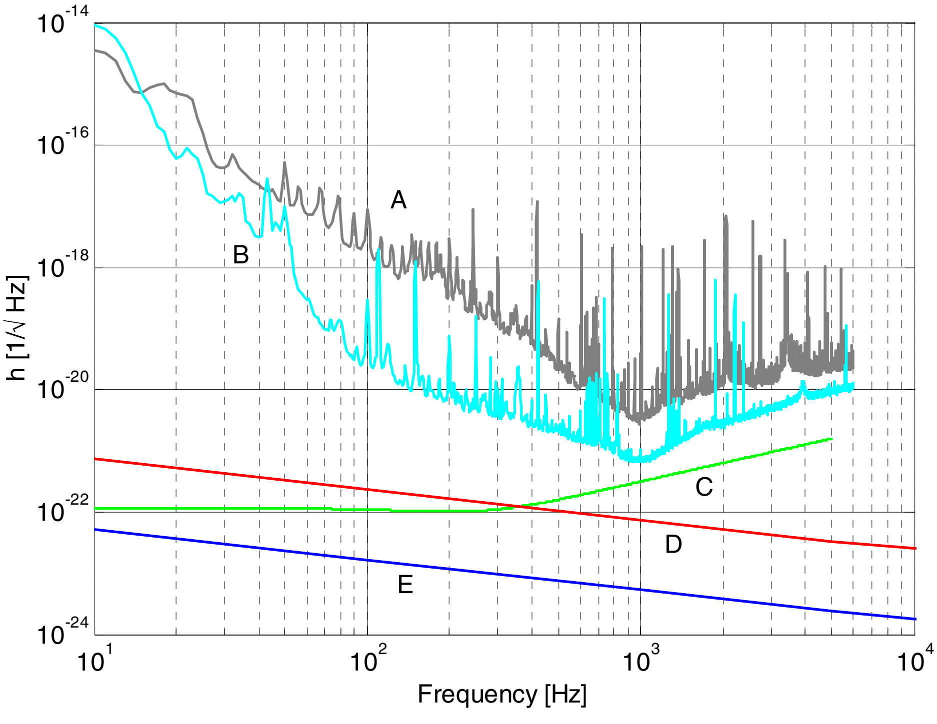

Figure 5: FEA aided estimation of the improvement of the thermal noise limit (D, E) of gravitational wave detectors (here: GEO600) using cryogenic techniques in comparison to the shot noise limit (C) and recent total noise curves of GEO600 (A, B).
A – GEO600 science run S3 total noise [16], B – GEO600 science run S4 total noise [16], C – shot noise limit [16], D – thermal noise limit @ 300 K ($Q = 3.8\times10^{6}$), E – thermal noise limit @ 10 K ($Q = 10^{8}$).

4. Conclusion

As the sensitivity of the interferometric gravitational wave detectors improves rapidly, a further growth rate of about one order of magnitude per year will soon strike the detector to its fundamental noise limits. Using cooled interferometer parts with higher Q-factors at low temperatures the thermal noise will be decreased strongly. In combination with high laser power to reduce the shot noise a much better sensitivity can be achieved. That would be a great step towards gravitational wave astronomy.

A special cryogenic system for the measurements of the mechanical Q-factor was built. It allows the investigation of the Q-factor dependence on temperature within a range of 5 K to 300 K. As a first attempt the well-known substrate material crystalline quartz was used to characterize the setup. Besides this, first measurements on silicon – a promising candidate for a substrate material – were done. Q-factors greater than 1×10^8 were achieved at cryogenic temperatures. This would provide an estimated sensitivity enhancement of at least one order of magnitude if applied to gravitational wave detectors.

Acknowledgement

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