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Mechanical Q-factor measurements on a test mass with a structured surface

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Abstract. We present mechanical Q-factors (quality factors) of a crystalline quartz test mass with a nano-structured surface, measured in the temperature regime from 5 to 300 K. The nano-structure was a grating with a period of 2 μm and a depth of about 0.1 μm. Comparative measurements were performed on the plain substrate and on the structured test mass with different numbers of SiO_2/Ta_2O_5 coating layers. The measurements at different stages of the test mass fabrication process show that the surface distortion induced by the nanostructure does not severely lower the mechanical Q-factor of the substrate. Damping due to a multi-layer coating stack was found to be orders of magnitude higher. The results provide vital information concerning the potential usage of low-thermal noise nano-structured test masses in future generations of high-precision laser interferometers and in current attempts to measure quantum effects of macroscopic mirror oscillators.

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Contents

1. Introduction

Currently operating high-precision laser interferometers such as the gravitational wave (GW) detectors GEO600 [1], VIRGO [2], LIGO [3] and TAMA [4] are among the most sensitive measurement devices ever built. They achieve noise spectral densities for differential length measurements as low as $10^{-18}\,\mathrm{mHz}^{-1/2}$ at frequencies of a few hundred hertz. Suspended test mass mirrors with high mechanical Q-factors are crucial prerequisites of these instruments to assure a low thermal noise floor in the detection band of the instrument. Future generations of GW detectors aim for orders of magnitude higher sensitivities and a further reduction of the thermal noise floor is required. Thermal noise of test masses is also a major problem in current attempts to observe quantum mechanical effects of macroscopic mirror oscillators. Further reduction of the thermal noise could enable the first observation of the ground state of a mirror oscillator visible to the unaided eye [5].

To reduce thermal noise, test masses with high-reflection nano-structured grating surfaces were proposed [6]–[8]. Firstly, such test masses allow for the operation of complex interferometric experiments without transmitting laser beams through the test masses (all-reflective interferometry). Beam-splitters as well as couplers to resonators can be substituted by appropriately designed reflection gratings [9]. Without any laser beam transmission, thermal noise from the temperature dependent test mass refractive index is avoided. Hence, laser beam absorption in the test mass is greatly reduced enabling cryogenic cooling of the test mass to generically reduce all types of thermal noise coupling. Secondly, nano-structured grating surfaces of test masses have been proposed to reduce the thermal noise from high-reflection multi-layer coating stacks on test mass mirrors [8]. In this scheme, the high-reflection test mass surface consists of a single thin coating layer in which a grating is etched to form a waveguide structure with up to 100% reflectivity.

In recent experiments low-loss dielectric high-reflection gratings were used in all-reflective interferometers [10, 11]. The period of the grating grooves was in the order of the laser wavelength $\lambda = 1064$ nm whereas the groove depth varied between 40 nm and roughly 1 μm. However, so far it has not been investigated whether all-reflective interferometry on the basis of nano-structured surfaces is compatible with the requirement of test masses to have high mechanical Q-factors. Besides internal dissipation processes in the bulk material, the mechanical loss of a test sample is heavily dependent on its *surface* quality. Rough surfaces cause phonon scattering resulting in lower Q-factors. By etching an optical grating structure, the surface of the test sample as well as the surface quality of the substrate can change significantly.

Figure 1. Schematic of the reflective nano-structured surface investigated in this paper. After the plain test mass substrate was investigated (1), a grating was etched into the substrate (2) using reactive ion beam etching. The structure was then overcoated by a single layer of SiO_2 (3) and then in the final step by a highly reflective layer stack (4).

In this paper, we present the first Q-factor measurements of a test mass with a nano-structured surface. We consider a broad temperature regime down to 5 K and show that nano-structured surfaces strongly support the endeavour to fabricate low thermal noise test masses with high Q-factors.

2. Test mass preparation

For our investigations, we chose a cylindrical test mass of 76.2 mm diameter and 12 mm thickness made from crystalline quartz. The size of the test mass, as well as the material chosen, enable the measurement of high Q values and are therefore suitable to reveal the influence of a nano-structured surface in a dedicated experiment which we describe in the next section. All mechanical Q-values were measured on the same test mass sample, but at different stages of preparation. The first measurements were performed on the plain test mass with all surfaces polished. The second measurement series was done with a grating structure etched into one of the test mass surfaces. The third measurement series was done with a 200 nm silica coating layer on top of the grating structure, and the fourth with an additional high reflection coating stack from silica and tantala. A schematic drawing of the cross-section of the final test mass is given in figure 1.

Reflection gratings used in [10, 11] were fabricated by employing electron-beam-lithography in order to provide the highest optical quality. However, the current high-precision electron-beam-writers are not capable of handling substrates with thicknesses of more than a few millimetres as required for high-Q measurement. Therefore, we decided to use laser-direct-writing for the grating pattern generation, which results in patterns of much lower optical quality, but with feature sizes comparable to those used in [10, 11]. For laser-direct-writing the substrate was coated with a thin layer (300 nm) of a UV-sensitive polymer. In this layer, a grating structure with a period of 2 μm was first written by a laser-beam. Reactive ion-beam etching was then used to etch the grating into the quartz test mass. The grating was centred and had a circular area of 50 mm diameter. The groove width was 1 μm and the groove depth was 115 nm. An atomic force microscope image of the grating is shown in figure 2.

The dielectric layers on top of the grating were commercially coated. The 200 nm SiO_2 layer was coated using electron beam evaporation. The high-reflectivity (HR) layer stack was coated

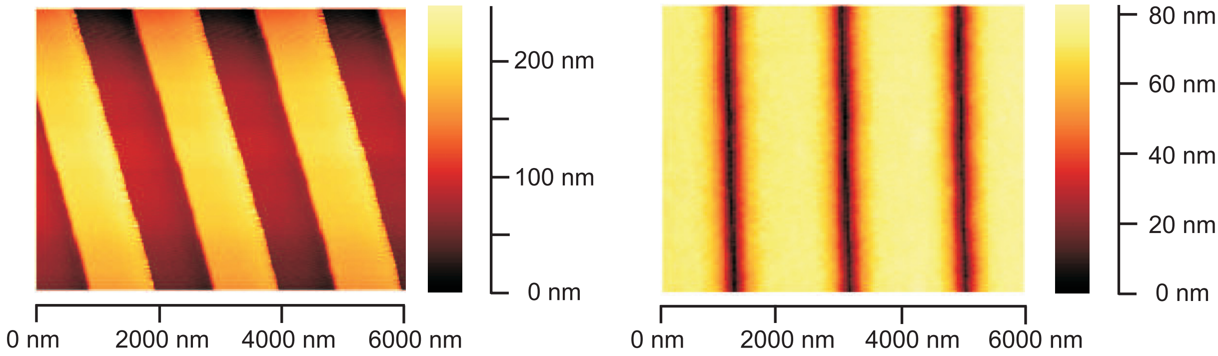

Figure 2. Left: atomic force microscope scan of the structured test mass surface without coating. Right: atomic force microscope scan of the final test mass with coating. By overcoating the grating structures with the high reflective stack the grooves were clearly washed out.

using magnetron sputtering. The HR coating was the final step of the test mass preparation and was composed of 36 alternating layers of 190 nm SiO_2 and 140 nm Ta_2O_5.

3. Mechanical *Q*-factor measurements

The mechanical Q-factors of the test mass sample were determined using ring-down experiments. The test mass was prepared stepwise as described in the previous section and, after each step, suspended as a pendulum by means of a tungsten wire in a custom made cryostat [12]. In each case, the test mass was carefully adjusted to provide the highest mechanical Q-factor possible. In this way we were able to reproduce the Q-values within an error bar of less than 10%. Further details of the experimental set-up and the measurements can be found in [13]. After having reached the desired measurement temperature the test mass was excited to resonant internal vibration at about $f_0 = 11$ kHz (a so-called butterfly mode [14]) using an ac voltage applied to an electrostatic actuator. The exponential free decay of the resonant vibration was measured with a laser interferometer after switching off the exciter. The amplitude decay to $1/e$ of the initial value is the ring-down time τ which can be used to calculate the mechanical Q-factor of the resonant mode at frequency f_0:

$$Q = \pi f_0 \tau. \tag{1}$$

The mechanical loss ϕ at a resonant frequency f_0 is given by

$$\phi(f_0) = \frac{1}{Q(f_0)}. \tag{2}$$

If the test sample consists of two dissipative parts (e.g. the substrate material and a coating/grating layer) the overall Q-factor can be estimated using the following relation [15, 16]:

$$\frac{1}{Q_{\mathrm{total}}} = \frac{1}{Q_{\mathrm{substrate}}} + \frac{E_{\mathrm{layer}}}{E_{\mathrm{substrate}}}\phi_{\mathrm{layer}}. \tag{3}$$

Table 1. Summary of the energy ratios between the different dissipative layers and the bulk material obtained from numerical calculations using ANSYS [17]. The errors of the calculation are about 15% due to the uncertainties in the layer properties and their temperature dependence. The elastic constants were taken from [18][5].

Ratio	Value
$E_{\mathrm{grating}}/E_{\mathrm{substrate}}$	8×10^{-5}
$E_{\mathrm{SiO_2}}/E_{\mathrm{substrate}}$	4.9×10^{-4}
$E_{\mathrm{HR}}/E_{\mathrm{substrate}}$	2.0×10^{-3}

Here, Q_{total} is the overall Q-factor, $Q_{\mathrm{substrate}}$ the Q-factor measured for the pure substrate material, and ϕ_{layer} is the mechanical loss of the thin dissipative layer. It is common to use the mechanical loss ϕ for layers rather than the Q-factor. $E_{\mathrm{layer}}/E_{\mathrm{substrate}}$ is the ratio of the mechanical strain energy between the thin layer and the substrate material during deformation. The ratio contains information about the geometry of the substrate and the layer. This ratio increases with coating thickness and coating diameter. For thin coating layers the ratio increases linearly with the coating thickness. Thus, it is possible to estimate the total mechanical Q-factor of a future real sized mirror from our results obtained from smaller test masses. The ratio was calculated via finite element analysis (FEA) using ANSYS [17]. For this calculation, the elastic constants were assumed to be temperature independent for simplicity. The accuracy of this assumption is sufficient for a rough approximation. The temperature dependent elastic parameters of the layers were unknown. The Youngs modulus for the SiO_2-layer was assumed to be the one of fused silica and was taken from [18]. The parameters for the dielectric layers of the HR coating were also obtained from [18]. The energy ratios are summarized in table 1.

4. Results and discussion of loss contributions

Figure 3 compares the measured mechanical Q-factors for four steps of test mass fabrication. The plain test mass substrate showed a Q-factor of greater than 10^8 at about 6 K (red circles). At 35 K all measurements revealed a rather poor mechanical Q-factor of as low as 5×10^4. Here, internal damping mechanisms dominate which were caused by impurities of the crystalline quartz substrate [14]. In the following, we discuss the loss contributions of the different preparation steps of the test mass surface.

The temperature dependent mechanical Q-factors of the pure substrate and the substrate with an etched grating were found to be identical within the measurement error of about 10%. Thus, applying a grating structure with groove width in the micrometre range and a depth of about 100 nm as needed for optical applications did not reduce the mechanical Q-factor by a measurable amount. Nevertheless, below 30 K a slightly lower mechanical Q-factor could be observed on the grating structure. Since this effect is within our error bars it is not clear if this effect can be attributed to the grating structure. By solving (3) for ϕ_{layer} and using the energy

[5] The properties of the substrate material were obtained from the datasheet of crystalline quartz from http://www.korth.de.

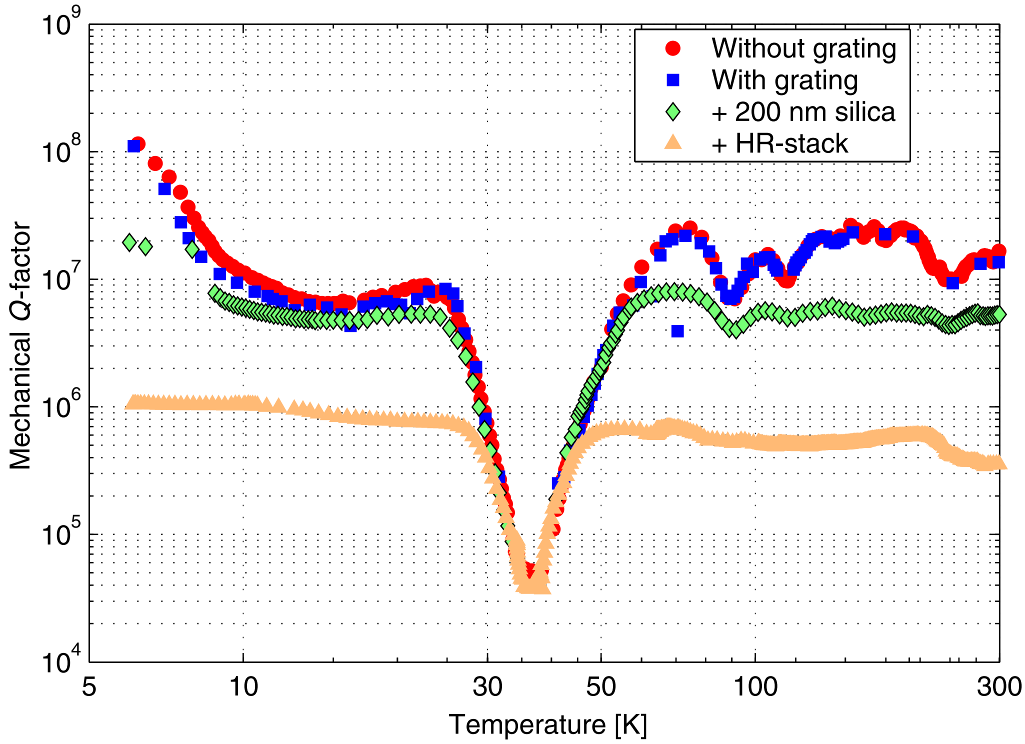

Figure 3. Compilation of altogether 300 mechanical Q-factor measurements. Every measurement lasted for 1 min to about 1 h. The four different symbols correspond to measurements on the same sample after different fabrication steps. In all cases the vibrational mode at 11.7 kHz was studied. All values are within an estimated error range of approximately 10%.

ratio between the grating layer and the substrate, it is possible to approximate the loss introduced by the applied grating below 30 K. The resulting loss is about one order of magnitude lower than the losses of dielectric coatings applied to substrates to form conventional mirrors.

When the SiO_2-layer had been applied, the overall mechanical Q-factor decreased significantly within the temperature range from 300 K down to 5 K. With an additional HR-stack the measurement was completely dominated by the coating. Apart from the 35 K damping peak of the substrate, no characteristic substrate peaks were visible. The measurement revealed a nearly temperature independent behaviour with a mean mechanical Q-factor of about 5×10^5. Only at temperatures below 20 K did the total mechanical Q-factor increase slightly with decreasing temperature to about 1×10^6 at 10 K.

Using (3) it is possible to determine the internal loss of a dielectric layer from the measured Q-factors of the substrate with and without the specific layer. Figure 4 (left) summarizes the results for the HR stack and the SiO_2 layer. The mechanical loss of the HR stack does not vary by orders of magnitude while cooling to cryogenic temperatures. At 10 K the mechanical loss of the highly reflective stack is about 4×10^{-4} at a measuring frequency of 11.7 kHz. This is comparable to the values reported by Yamamoto *et al* [20] at low temperatures measured at 1.1 and 2.5 kHz. The lowest mechanical loss of a HR stack reported till now is around 2×10^{-4} obtained from a tantala/silica HR stack [21]. The tantala was doped with approximately 20% titania (Ti-ion concentration).

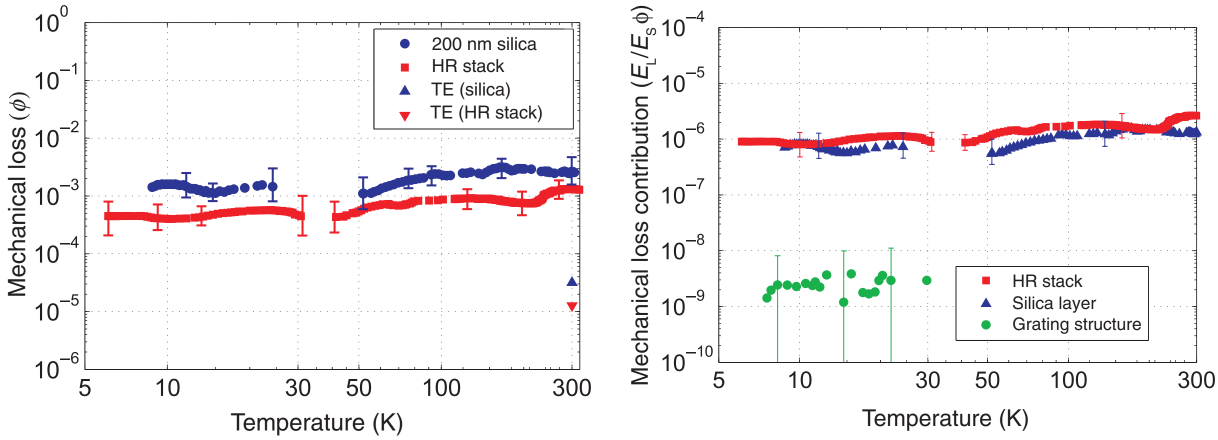

Figure 4. Left: comparison of the mechanical losses of the HR stack and the SiO_2 layer. Additionally the thermoelastic loss of the layers is given. Around 35 K the substrate damping dominates the measurements and the measurement errors for the coating losses are increased greatly. Therefore, results are only given for points far away from that region. The thermoelastic loss (TE) contribution of the different layers was calculated and plotted only for 300 K and 11.7 kHz. Error bars are given for some specific temperatures. Right: compilation of the loss contribution for the different fabrication steps. The plot represents the intrinsic loss weighted by the energy ratio between the layer and the substrate. The grating structure has only a small influence on the total mechanical loss of the test mass. The HR stack loss dominates in the final device.

The total loss ϕ_{layer} of a coating generally consists of two contributions: the mechanical intrinsic loss $\phi_{\text{intrinsic}}$ of the film and the thermoelastic loss ϕ_{TE} of the film:

$$\phi_{\text{layer}}(f) = \phi_{\text{intrinsic}}(f) + \phi_{\text{TE}}(f). \tag{4}$$

The thermoelastic loss arises from the different thermo-mechanical properties of the substrate and the coating material. It is useful to estimate the thermoelastic loss of the coatings in order to check if the values obtained from our measurements are dominated by intrinsic or thermoelastic processes.

The calculation of the thermoelastic contribution of thin layers are given by Fejer *et al* [18]. Using the specific equations for a single layer and a multi layer[6] it is possible to estimate the thermoelastic loss of the coatings. The numerical calculation was made only at 300 K. Even at this temperature it is not possible to find all required data in the literature. Especially thermal data for thin films at low temperatures are not available. The calculated thermoelastic loss limit for both the SiO_2 and the HR coating are two orders of magnitude lower than the intrinsic mechanical loss obtained from our measurements. Hence, the measurements presented in this paper are not limited by thermoelastic loss and therefore represent the intrinsic loss of the coating itself.

Figure 4 (right) represents the different loss contributions obtained from our measurements. The intrinsic loss is weighted by the energy ratio of the layer and the substrate material taking

[6] To calculate the thermoelastic loss of the silica single layer and the HR stack equation (37) and (42) in [18] were used.

their thicknesses into account. Thus, a comparison between the different loss contributions is easily possible. The loss introduced by the thin grating structure is more than two orders of magnitude lower than the loss caused by the dielectric coatings. Therefore, the contribution of the grating is negligible compared to the coatings.

It can be concluded from our results that a precisely etched grating structure does not produce random scattering centres for the phonons decreasing the mechanical Q-factor for the observed mode. Scaling up the mirror test mass size to several tens of kilograms as envisaged for the next generation GW detectors, the energy ratio in (3) will be decreased, and the influence of the grating to the total mechanical Q-factor will be lowered further.

5. Summary and conclusion

Cryogenic mechanical Q-factor measurements on a mirror test mass with a nanometre-size grating etched into its surface were presented for the first time. It was demonstrated that the grating structure did not significantly influence the overall mechanical Q-factor. A Q-factor of greater than 10^8 was measured on a crystalline quartz sample with nano-structured surface at a temperature of 6 K. Our results strongly support the idea of using reflective grating test masses as substitutes for conventional optical elements in low thermal noise interferometric measurements. The results of our low temperature loss measurements of dielectric coatings were comparable to the results of other groups. Thus, the coating thermal noise is indeed a problem unless thin grating waveguide coatings [8] are available.

Acknowledgments

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