Thermal noise reduction for future gravitational wave detectors

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Abstract. The coating thermal noise limits the sensitivity in gravitational wave detectors from few tens to hundreds Hz, where first gravitational signals were detected and others are expected. In view of future upgrades, the increase in the mechanical performances of reflective coatings, retaining their outstanding optical and morphological properties, is fundamental. In the Virgo collaboration a coating R&D group working with this aim is born. One of the research lines regards the mechanical characterization of both substrates and coatings, looking for materials with low mechanical loss angle. To perform a precise coating mechanical characterization, the substrate on which it is deposited must be characterized as well and must be stable with respect to its dissipative behaviour. Commercial SiO$_2$ substrates are subject to effects that change their mechanical condition during time, compromising the characterization. The source of these spurious losses is related to the rough lateral surface: after its polishing, this behaviour is largely reduced. We designed and assemble a facility for the CO$_2$ laser polishing of the substrates barrel, to provide a reliable heat treatment, reducing spurious losses to a negligible level. Other further treatments have been tested, with the aim of taking under control $\phi$ deterioration. We develop a procedure to prepare SiO$_2$ samples for coating deposition. Procedure steps, mechanical characterizations and first results are shown.

1. Introduction
On September 14$^{\text{th}}$ 2015 a Gravitational Wave (GW) coming from binary black holes coalescence was detected for the first time [1], a hundred years after their prediction by Einstein. Five other similar signals and a signal from binary neutron stars merger were detected, both by Advanced LIGO and Advanced Virgo interferometers [2]. The network of the three detectors all together allowed to significantly improve distance measurement and sky localization [2, 3] and the binary neutron stars signal was also followed by detection of electromagnetic counterpart, arrived to the Earth 1.7 second after [4].

Enhance the sensitivity of interferometric detectors is needed to obtain greater numbers of detections at lower noise levels, opening the doors to GW astronomy. Both current and future interferometers, in the middle frequency band, from few tens to hundreds Hz, are limited by mirror thermal noise. The main contribution to this noise is Coating Thermal Noise (CTN), related to structural dissipation inside the multilayer dielectric coatings [5]. The reduction of this noise is fundamental for advanced detectors. More generally, finding a way to reduce CTN would be beneficial also for other precision experiments using high-finesse optical cavities, such as frequency standards for laser stabilization, quantum computing devices and opto-mechanical resonators.
2. Thermal noise in GW detectors

The first observation of thermally-driven displacement was by Brown in 1828 [6] and it took almost a century to develop a full mathematical treatment of Brownian motion by Einstein [7]. Nowadays it is known that any parameter characterising a dissipative system will exhibit spontaneous thermal fluctuations, as described by the Fluctuation-Dissipation theorem [8]. From the theory it is possible to derive that the thermal noise power spectral density $S_x$ of the system’s displacement $x(t)$ is inversely proportional to the real part of the mechanical impedance of the system:

$$S_x(f) = \frac{k_B T}{\pi^2 f^2 \text{Re}\{Z(f)\}},$$

(1)

where $T$ is the temperature, $k_B$ is the Boltzmann constant, $f$ is the frequency, and $Z(f)$ is the system mechanical impedance [9]. These thermal fluctuations are represented by the damping coefficient of the system. Particularly, internal damping effects (i.e. internal frictions) arise from the anelasticity of the system itself: when a stress is applied, the strain response is not instantaneous. The stress-strain phase lag is the system damping coefficient of interest, that is the mechanical loss angle, defined as $\phi(f_0) = E_{\text{ipc}}/2\pi E_{\text{tot}} = \Delta f/f_0 = 1/Q$, where $E_{\text{tot}}$ is the total energy stored in the oscillation system, $E_{\text{ipc}}$ is the energy lost per cycle of the oscillation, $\Delta f$ is the width of the resonance peak and $Q$ is the mechanical quality factor. The work carried out by Levin [10] apply the general description to the case of the thermal noise of the mirrors and coating for the GW detector:

$$S_{\text{TN}}(f) = \frac{2k_B T}{\sqrt{\pi} f w Y_{\text{sub}}} \left( \phi_{\text{sub}} + \frac{2}{\sqrt{\pi}} \frac{1 - 2\sigma}{1 - \sigma} d w \phi_{\text{coat}} \right),$$

(2)

where $w$ is the radius of the laser beam at the mirror surface, $Y_{\text{sub}}$ and $\sigma$ are respectively the material Young’s modulus and the Poisson’s ratio and $d$ is the coating thickness. The dominant part of mirror thermal noise is the one from the high reflecting coating. To reduce the CTN, one can act on (see Eq. 2) temperature (going cryogenic), coating thickness (increasing the index of refraction), laser spot dimension (to be increased), or finally coating loss angle $\phi_{\text{coat}}$ (to be reduced).

2.1. Coatings state of art

GW detectors high-reflection coatings are Bragg reflectors, composed of alternate layers of ion-beam-sputtered fused silica ($\text{SiO}_2$) and titania doped tantala ($\text{Ti:Ta}_2\text{O}_5$) as low- and high-refractive-index materials [11]. The coatings are designed and deposited in the Laboratoire de Matériaux Avancés (LMA), in Lyon, and allow to lose less than 0.0001% of the light impinging on them, having very low absorption and scattering (Tab. 1). They are the most advanced optics in the world.

| Flatness       | $<0.5$ nm RMS (within $\odot$ 150 mm) |
|----------------|---------------------------------|
| Thickness uniformity | 0.05% (within $\odot$ 150 mm) |
| Absorption     | $<0.4$ ppm                      |
| Scattering     | $<10$ ppm                       |
| Coating material (at 1064 nm) | Reflective index | Loss angle |
| $\text{SiO}_2$ | 1.45±0.01                  | (4.5±0.3)e$^{-5}$ |
| $\text{Ta}_2\text{O}_5$ | 2.03±0.02         | 3e$^{-4}$   |
| $\text{Ti:Ta}_2\text{O}_5$ | 2.07±0.02         | (2.4±0.3)e$^{-4}$ |

Nonetheless, the mechanical losses (related to the $\text{Ta}_2\text{O}_5$ layers) are still at an high level and need to be reduced for future upgrades of GW detectors.
3. The Virgo Coating R&D collaboration
In the last decade, the path toward lower noise coatings starts to get clearer, thanks to national and international research projects, together with the theoretical guidance and technological expertise growth. Inside the Virgo collaboration the need to reduce CTN has been stressed and recently a collaboration started to work hardly on it: the Virgo Coating R&D (VCR&D) collaboration. It is made up of many research groups of the Virgo collaboration (both from Italy and France) and has within it coating deposition technologies, internal friction measurements facilities, optical and structural characterization facilities. Furthermore, the members of this collaboration have developed the nowadays employed multilayer reflective coatings and have a leading role in the world research on low-noise coatings.

VCR&D group works on many subjects, especially metrology (mechanical characterization, thermo-elasticity calculation) new coating materials (new oxides, nitrates, fluoride, new mixing and nano-layered composites), deposition parameters, with the aim of developing new multilayer reflective coatings for the Advanced Virgo upgrades and new technologies for future detectors. In this work the procedure for the mechanical characterization of the coating, achieved by loss angle measurements, is shown.

4. Low-loss material mechanical characterization
As shown through eq. 2, one way to reduce CTN is lowering coating loss angle $\phi_{coat}$. This can be done finding new materials or mixtures with lower mechanical losses or improving mechanical losses research in current coating materials. In both cases, a way to mechanically characterize coating loss angle is through a differential measurement that follow this formula [15]:

$$\phi_{coat} \approx \frac{Y_{sub}d_{sub}}{3Y_{coat}d_{coat}} (\phi_{sub+coat} - \phi_{sub}),$$  \hspace{1cm} (3)

where $Y$ and $d$ are Young's moduli and thickness of substrate and coating. Therefore to analytically extract the coating loss angle, is necessary to mechanically characterize a sample both before and after the coating deposition. In this perspective, it is fundamental to have a well defined characterization procedure of the substrates.

4.1. Ring-down method and Gentle Nodal Suspension
The mechanical characterization of substrates and coatings can be performed studying small disk-shaped samples, on which different coatings material can be deposited. The $\phi$ measurements are performed through the ring-down method, exciting the resonant mode of the sample and measuring the exponential decrease in the free oscillation amplitude:

$$\phi = \frac{1}{\pi f \tau}.$$  \hspace{1cm} (4)

This implies that the sample has to be held by some kind of suspension or clamping, making the coupling between the two negligible. The Gentle Nodal Suspension (GeNS) system [16], is worldwide recognized as one of the most powerful tool for mechanical characterization. In GeNS, a disk shaped sample is placed in equilibrium from its centre on top of a sphere, that provides a mechanically stable support (Fig. 1).
GeNS allows to avoid the clamping of the samples, suppressing any potential additional source of damping; only one of the two faces is touched and the contact area is minimized. Furthermore coated surfaces are not damaged and all mode families with nodal lines passing through the centre of the sample can be measured.
4.2. Fused silica substrates issues
Fused silica substrates have always shown a particular behaviour in the losses distribution. It has been shown that their loss angle depends on the modes, following a distribution into families [17]; furthermore these substrates can also suffer loss angle variation over time due to ageing effects and absorption of contaminants. In Fig. 2 there is an example of these effects: in all the coloured series the separation in two branches (depending on the belonging family) is evident, on top all butterfly modes (only azimuthal nodal lines) on bottom all mixed modes (both azimuthal and radial nodal lines); following the colour sequence (blue - red - green - yellow) also the ageing/contamination effects are shown.

Figure 2. Loss angle dependence on frequency and mode families [18] for a SiO$_2$ sample produced by Corning of 3 inches diameter. Blue dots are the initial mechanical characterization, while red ones show the ageing effects (55 days later). Green dots are the characterization after an annealing treatment. In yellow the last characterization, that shows that the annealing does not stop ageing effects definitively.

In [17] a model that justify the existence of this family branching and predicting the level of losses is presented. The phenomenon could arise from excess losses inside the rough, not polished edge of the commercial samples and interests mainly the butterfly modes. All these issues makes the characterization of the SiO$_2$ substrate not easy. In the following a strategy to solve these issues is shown.

5. Fused silica substrates preparation and characterization procedure
Due to the analytical method used to extract coating loss angle and also due to the issues of fused silica substrates, a precise procedure to prepare and characterize the samples is needed. It includes many mechanical characterizations through GeNS, and different preparation procedures regarding the SiO$_2$ substrate, like polishing of the lateral surface, annealing and vacuum storage. To reduce effects described in Section 4.2, a facility for the CO$_2$ laser polishing of the substrates barrel has been designed and realised in the Roma Tor Vergata University [19]. It includes:

- a CO$_2$ laser (maximum power $P_{\text{max}} = 15$ W),
- a red LED, for the alignment of the CO$_2$ beam,
- a lens (=150 mm), to adjust the CO$_2$ beam dimension,
• two galvo mirrors, to steer the CO\textsubscript{2} beam and perform many heating patterns,
• a rotary stage with a step motor, to rotate the samples during the polishing procedure.

In Fig. 3 it is possible to see the optical bench layout and some details of the components. With this facility it is possible to freely choose the set of parameters of the polishing process to optimize it, like rotation rate, number of rounds, heating pattern, beam power and beam size.

![Figure 3. Optical bench layout of the CO\textsubscript{2} polishing facility in the University of Roma Tor Vergata, with details of part of the components, like galvo mirror heating patterns and rotary stage.]

Other two procedures have been identified having effects on sample losses:

• annealing of the sample, consists of a thermal heating of the whole disk at high temperatures; for this procedure the sample has to be put inside a suitable container to protect it from any contamination that can arise during the heating; it allows to relax the structural frictions inside the samples;

• vacuum storage (still under study), consists of the storage of the samples in vacuum chamber for a suitable period; probably allows to de-absorb contaminants inside the unpolished (or not perfectly polished) lateral surface.

The effects of all the procedures can be quantified through mechanical characterization of the substrates. In Fig. 4 the mechanical characterizations of two different fused silica samples are shown: in each plot can be seen the CO\textsubscript{2} polishing effect on the sample mechanical losses (from blue initial characterization to green one). Particularly in Fig. 4(b) one can see that the CO\textsubscript{2} polishing of the barrel allows to maintain the sample losses almost stable in time.

6. Conclusions

Fused silica substrates can suffer loss angle variation over time due to different mechanisms, still under study. Their mechanical characterization is of fundamental importance to obtain a reliable estimation of the deposited coating loss angle.

A procedure to minimize or eliminate these loss angle variations and to mechanically characterize the substrates has been outlined. The substrate must undergo to a series of steps:

• initial mechanical characterization,
• CO\textsubscript{2} barrel polishing,
• annealing treatment and/or vacuum storage,
• second mechanical characterization.

This procedure has been already tested on some samples, showing good results in reducing both branching and ageing effects: looking at Fig. 4 the branching between butterfly and mixed
Figure 4. (a) Mechanical characterization for a SiO$_2$ sample produced by Corning of 1 inch diameter. In blue, initial characterization; in pink effect of the annealing procedure; in light blue effect of the vacuum storage; in green effect of the polishing procedure. (b) Mechanical losses in a Suprasil Impex SiO$_2$ substrate of 2 inches diameter. In blue the initial characterization; in green the effect of the polishing procedure; in red the characterization made 10 month after the CO$_2$ polishing. In both plot, B stands for butterfly modes and M stands for mixed ones.

modes measured in different moments is reduced after the polishing procedure; furthermore, the measurements in Fig 4(b) shows that after one year mechanical losses remain constant, without ageing effects.

More investigation on annealing and vacuum storage is needed and further improvements of CO$_2$ polishing procedure are possible.

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