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Coating mechanical and optical losses in gravitational wave detectors

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Abstract

Mirror coatings play a crucial role in the performance of laser interferometers devoted to gravitational wave detection such as Virgo and LIGO. Mechanical losses in the coating material limit the sensitivity of the detectors due to the associated mirror thermal noise. The absorption of light in the coating induces a thermal lens in the mirror substrate which reduces the quality of the optical interference and requires sophisticated thermal compensation systems. This paper describes the work ongoing at LMA in order to reduce mechanical losses and optical absorption in the coating. The results obtained by doping the Ta_2O_5 layers and testing different high index materials are described. Finally the performances of different potential coatings are compared and the results obtained with a 40 kg mirror are reported. Titania doped Ta_2O_5 shows mechanical losses of 2 10^{-4} and absorption below 0.5 ppm. Nb_2O_5 appears to be the best competitor from the thermal noise point of view but it has an optical absorption 4 to 5 five times larger.

1 Introduction

Mirror coatings play a crucial role in the performance of laser interferometers devoted to gravitational wave detection such as Virgo [1] and LIGO [2].

Mechanical losses inside the coating limit the sensitivity of the detectors due to the associated mirror thermal noise. This noise is one of the limitations to the sensitivity of Virgo and LIGO and it is expected to remain the main limitation in the sensitivity of advanced detectors to gravitational waves with frequencies around 100 Hz [3].

Another important aspect connected with the coating properties is the absorption of light inside the coating material. The absorption of light induces a thermal lens in the mirror substrates which reduces the quality of the optical interference. In the end this effect limits the amount of laser power that can be stored in the interferometer and, as a consequence, the sensitivity of the detectors at frequencies above a few hundreds Hz where the limitation comes from the shot noise. To correct for these effects sophisticated thermal compensation systems have been developed [4]. This has been one of the major difficulties encountered in the commissioning of LIGO and Virgo and will require the implementation of more complex thermal compensation devices in the advanced detectors [3].

For several years the effect of the mechanical losses inside the coating was not considered and the focus was put on the optical absorption. Both initial LIGO and Virgo used multi-layers coatings made of silica as low index material and of tantalum pentoxide (or tantala) as high index material. The reason for this choice was mainly driven by the low absorption of the tantalum pentoxide at the used wavelength (1064 nm). The use of this material allows reducing the coating absorption to about 1 ppm [5].

At the end of the nineties it was realized that the mirror mechanical losses were limited by the mechanical dissipation in the coating [6, 7]. Moreover the test of different types of coatings showed that the losses came from the mechanical dissipation inside the high index material, namely the tantalum pentoxide [8,9,10]. The losses were measured at several different places and turned out to be in the range of 3 to 5 10^{-4} depending on the coating manufacturer. These values are about one order of magnitude larger than those measured in the silica (i.e. the coating low index material).

For the above reasons it is important to minimize the mechanical losses in the high index material keeping the optical absorption as low as possible. These two parameters are the most important from the point of view of the gravitational wave detector sensitivity. But other parameters need to be kept under control. The ion beam sputtering technique is known to produce coatings which can have a high internal stress. This stress can induce a deformation on the substrate figure. It can also reduce the adherence of the coating on the substrate and be the cause of formation of defects inside the coating material. For these reasons it is important to measure the stress in the coating when new materials are tested.

The need to reduce the mechanical losses in the high index material was the main motivation for the development of titania doped tantalum pentoxide that was performed at LMA and that is reported in [11].

This paper describes the most recent development performed at LMA both on the tantala coatings and on different alternative materials. The experimental apparatus used to perform this development is described in section 2. Then the result obtained by doping the tantalum pentoxide layers are reported in section 3 together with the characterization performed on the best performing materials. Section 4 describes the results obtained with other high index materials tested at LMA. Finally the results are discussed in section 5.

2 Experimental apparatus

2.1 Coating chambers

In order to reduce the optical absorption it is important to reduce to a minimum the presence of impurities in the coating layers. Ion beam sputtering is the technique that allows producing the purest coating materials. An Ar ion source combined with an electron source (neutralizer) is used to produce a low energy neutral beam of Ar in a vacuum of 3 10^{-4} Torr. The Ar beam is directed against a target made of the material to be deposited (typically Ta or Si). Oxidation is realized by injecting oxygen in the chamber during the process. The sputtered material reaches the substrate where it condenses thus producing the required coating layer. By changing the target material one can produce alternate layers of low index and high index materials and realize the required multi-layer structure.

Two coating chambers of this type are used at LMA. The first coating chamber has a volume of 0.5 m^3 and is equipped with a Kaufmann ion source. This chamber can coat substrates as large as 3 inches in diameter and is equipped with a planetary support for the substrates. The second is a 10 m^3 chamber equipped with two RF sources and able to coat substrates up to 1 m diameter. The latter is the coating chamber which is used to produce mirrors for the Virgo interferometer [12].

2.2 Optical loss measurements

The optical absorption of single coating layers and multi-layer structures are measured taking advantage of the so called mirage effect. A 30 W Nd:YAG laser is chopped at a few hundreds Hz and is sent to the coating layer to be measured. The laser power absorbed in the coating produces a thermal gradient in the silica substrate which varies at the chopper frequency. A second low power He-Ne laser beam (probe beam) crosses the thermal gradient induced by the high power beam. The gradient in the index of refraction produces a deflection of the probe beam which varies at the chopper frequency. The position of the transmitted He-Ne laser is measured with a quadrant photodiode and a lock-in amplifier. This measurement combined with the proper calibration allows measuring coating absorptions with a sensitivity of 0.02 ppm. The same device can be used to measure bulk absorption with a sensitivity of 0.1 ppm/cm. By moving the sample across the two beams it is possible to produce maps of the absorption across samples as large as 400 mm. A more detailed description of this set-up can be found in [13].

2.3 Mechanical loss measurements

The mechanical losses of the coating are measured by studying their effect on the quality factor of thin silica cantilevers (Suprasil 311 from Heraeus). The cantilevers are 45 mm long, 5 mm wide and 110 μm thick. The cantilever geometry has been chosen such that its resonant modes are in the range of frequencies of interest for gravitational wave detectors. Once clamped at one end the fundamental resonant frequency is around 60 Hz, the 2nd and 3rd resonant modes are respectively at about 400 Hz and 1.1 kHz.

The mechanical quality factor of the cantilever resonant modes is measured before and after the cantilever is coated. By comparing these two measurements one can deduce the value of the mechanical loss of the coating. This requires knowing the ratio between the energy stored in the substrate and the energy stored in the coating that depends on their Young modulus and on their thickness.

In order to reduce the error on the coating loss measurement it is important to have the highest possible quality factor for the uncoated cantilever. To this purpose the cantilevers are annealed at 900^{o}C and cleaned. This process allows relaxing the stress, decreasing the internal density fluctuations and removing impurities left from the polishing process. It may be worth mentioning that the effect of annealing on silica mechanical loss has already been observed in the past [14,15]. Particular care is taken in the clamping of the cantilever. The clamp itself is polished before mounting a new cantilever. Both the surfaces in contact with the cantilever and at right angles are polished in order to have a sharp edge in contact with the cantilever and to reduce the Van der Walls forces between the clamp and the vibrating cantilever. Finally the cantilever is clamped very tightly. The cantilever and its support are placed in a vacuum chamber at 10^{-6} Torr in order to eliminate any dissipation due to the residual gas.

The cantilever position is measured by means of an optical lever which uses a low power He-Ne laser. The latter is reflected on the cantilever and is readout by a quadrant photodiode.

With this bench it is possible to obtain a quality factor for the first cantilever mode of the order of 250000. The residual losses are due to the clamp and are in the range of $4\ 10^{-6}$.

The same cantilevers are used to measure the stress in the coating. The principle of the measurement is relatively simple [16]. The curvature of cantilever is measured before the coating is deposited by means of an optical interferometric profiler. The comparison with the cantilever curvature measured after the coating is deposited allows deducing the stress in the coating.

3 Doping of the Ta_2O_5

The first class of attempts done to reduce the mechanical loss of the high index material consists in improving the tantalum pentoxide by doping it with other oxides i.e. materials that are known to have a good transparency to near infrared light. Several materials were tested to this purpose. Table 1 shows a summary of the measurements that were made on 500 nm thick monolayers of doped Ta_2O_5.

	Refraction index	Absorption (ppm)	Mechanical losses
Ta_2O_5	2.035	1.22	$3 \cdot 10^{-4}$
Ta_2O_5 : Co	2.11	5000	$11 \cdot 10^{-4}$
Ta_2O_5 : W	2.07	2.45	$7.5 \cdot 10^{-4}$
Ta_2O_5 : W+Ti	2.06	1.65	$3.3 \cdot 10^{-4}$
Ta_2O_5 : Ti	2.07	0.5	$2.4 \cdot 10^{-4}$

Table 1: Main parameters of coating monolayers made of tantala doped with different materials

In general the doping allows an increase of the refraction index of the material. This increases the contrast between the high and the low index materials thus reducing the amount of high index material that is needed to obtain a given reflectivity. As a consequence, if the mechanical losses are kept constant, the thermal noise would decrease. Unfortunately, as it is visible in the table, in most cases the optical and the mechanical losses tend to increase as well.

In the case of the doping with Co a very large increase of the optical absorption is measured. The doping with Ti+W shows a pretty low absorption and a promising mechanical loss but an attempt to coat a mirror with this material has shown a large optical absorption, probably due to some diffusion of material between the layers. The best results are obtained with Ti doping. In this case both the mechanical losses and the optical absorption decrease.

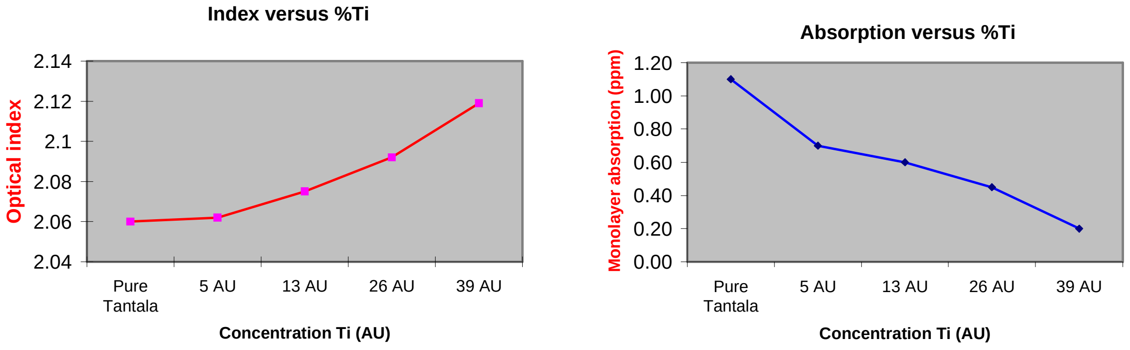

Figure 1. Refraction index (left) and absorption (right) of Ti: Ta_2O_5 as a function of the amount of dopant used in the chamber expressed in arbitrary units.

A study performed in the small coating chamber showed that by increasing the doping level it was possible to increase the index of refraction while decreasing the optical absorption. Figure 1 shows the index of refraction and the optical absorption as a function of the amount of doping material used in the chamber (expressed in arbitrary units).

A more detailed optimization was performed on the larger coating machine as the large mirrors needed by laser interferometer gravitational wave detectors are produced in this machine. By adjusting the parameters of the coating process it was possible to decrease the mechanical loss to about 1.9-2.0 10^{-4}. The best value ever measured was around 1.5 10^{-4} which is a factor of two better than the value of the undoped Ta_2O_5.

Two different levels of Ti doping were tested in the large coating machine.

A Rutheford backscattering analysis was carried on both materials to measure the different atoms concentration and thus the doping level. Samples of the coatings deposited on fused silica and silicon substrates were exposed to a 2.5 MeV He+ beam. The data were analyzed using the SIMNRA software [17]. This program is a montecarlo simulation including non-Rutherford backscattering, nuclear reaction analysis and elastic recoil detection analysis with MeV ions. About 300 different non-Rutherford and nuclear reactions cross-sections are taken into account.

First the undoped tantala coating was analyzed. This analysis shows that the ratio Ta/O corresponds to the good stoichiometry. The coating density is found to be 7.2 g/cm^3, which is about 12% smaller than expected for bulk Ta_2O_5.

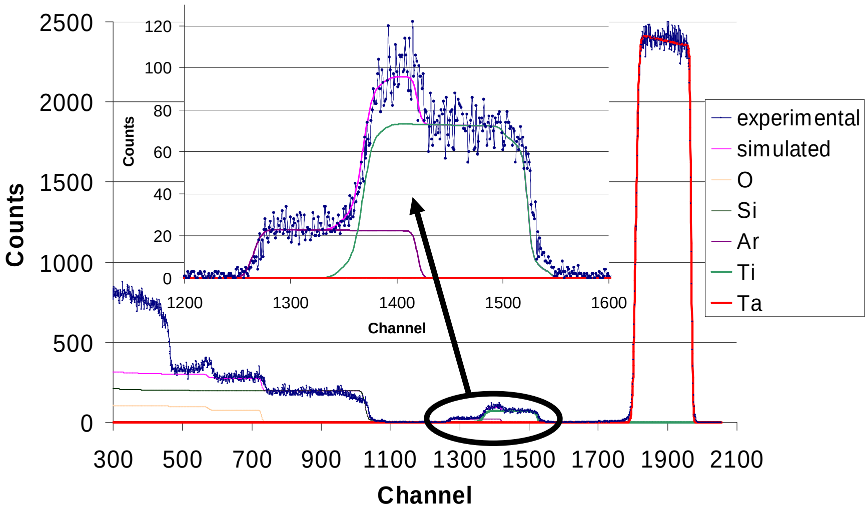

Figure 2. RBS spectrum of a Ti doped Tantala coating. The channel corresponds to the energy of the backscattered ions. This is calibrated using pure elements targets of Al, Ti, W and Zr. The peaks widths provide the density of the element in at/cm2 and the peaks height is related to the atomic concentration of the element. The insert shows a zoom of the region between 1200 and 1600, where are visible the signals given by the Argon and the Titanium. The large peak at higher energy is due to the Tantalum.

Subsequently the two Ti doped materials were analyzed: one of the resulting RBS spectra are shown in Figure 2. This analysis shows that the two samples have a ratio of Ta/Ti equal to 1.25 and 3. Their densities are equal to 6.4 g/cm3 and 5.5 g/cm3 respectively. These values are compatible with the measured atomic concentrations and with the density of the undoped tantala. The sample with more Ti has an index of refraction equal to 2.18 while the other has an index of refraction around 2.07 (for sake of comparison the un-doped tantala has n=2.035). On the other hand the coating with more Ti has also higher mechanical losses (~2.2 10^{-4} compared to ~1.9 10^{-4}) so that in the end the two materials have comparable performances in terms of coating thermal noise. The RBS analysis also reveals the presence of a small fraction of Ar in both types of coating. The Ar total atomic concentration was found to be in the range between 3% and 4% (corresponding to about one Ar atom for 6 to 7 Ta atoms in the case of pure Tantala). This is not surprising as Ar is used as sputtering beam.

The material with less doping was used to coat the first prototype of the Advanced LIGO mirrors. This is a 34 cm diameter and 20 cm thick mirror made of fused silica and having a weight of 40 kg. The deposited coating had a diameter of 300 cm and was made of 18 doublets of Titania doped Ta_2O_5 and SiO_2 in order to get a transmission of 10 ppm. The map of the coating absorption is shown in Figure 3. The average absorption of the coating is about 0.25 ppm. For sake of comparison the initial Virgo mirrors produced with standard tantala have absorption of about 0.7 ppm.

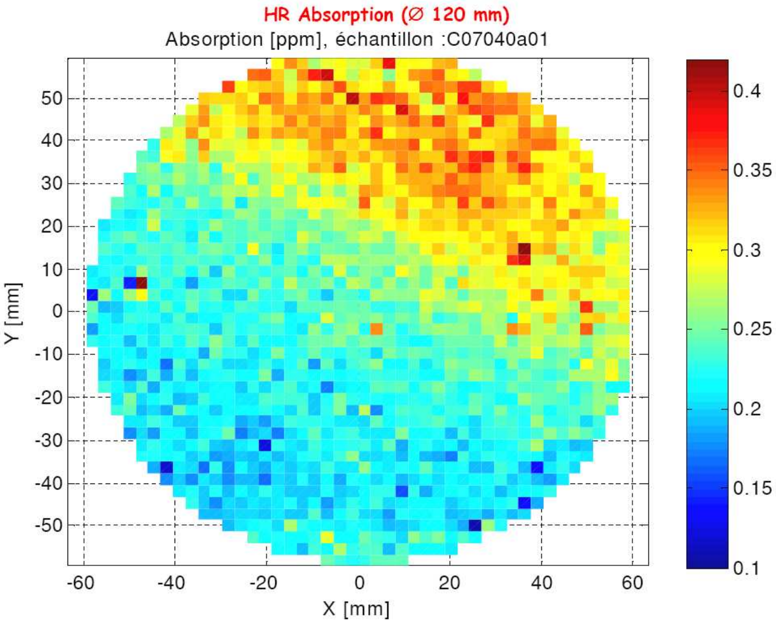

Figure 3. Map of the absorption of a Ti doped Ta2O5 coating measured over a 120 mm diameter.

4 Study of other high index materials

Another approach to reduce the mechanical losses in the coatings consists in replacing the Ta_2O_5 with another kind of high index material. Two materials have been studied to this purpose: zirconium dioxide and niobium pentoxide. Both materials were produced in the smaller coating chamber.

The ZrO_2 was first produced in its undoped form and then doped with titanium and tungsten. The results obtained are shown in Table 2. The index of refraction of ZrO_2 is relatively high (n=2.1) and its mechanical losses are lower than standard Ta_2O_5. Unfortunately the stress in the coating is quite high and this makes the production of multi-layers structures more critical. In addition the optical absorption is about ten times larger than that of Ta_2O_5.

Coating	Refraction index	Absorption (ppm)	Mechanical losses	Stress (MPa)
ZrO_2	2.10	11	$2.3 \cdot 10^{-4}$	-1780
ZrO_2 : Ti	2.15	37	$6.8 \cdot 10^{-4}$	-180
ZrO_2 : W	2.12	10	$2.8 \cdot 10^{-4}$	-600

Table 2. Measured coating parameters on monolayers of ZrO_2 , Ti doped ZrO_2 and W doped ZrO_2. A negative stress is a compressive stress.

By doping the Zr with tungsten it is possible to increase the index of refraction and strongly decrease the stress. Unfortunately both the mechanical losses and the absorption increase.

Doping with Ti gives intermediate results. The stress is decreased and the index of refraction is slightly increased. But the optical absorption remains quite higher than that of Ta_2O_5 and, contrary to what happens in the case of Ta_2O_5, the mechanical losses are worst than those of the undoped ZrO_2. In conclusion using ZrO_2 does not allow improving the performances compared to Ta_2O_5.

The Nb_2O_5 was studied only in its un-doped form. The refraction index is 2.21, considerably higher than that of Ta_2O_5. According to the literature it is possible to achieve even higher values [18]. This is of help from the thermal noise point of view as less material is required to achieve the same reflectivity. The optical absorption is 2.2 ppm, about twice that of Ta_2O_5. The same level of absorption was measured on a high reflectivity mirror made of 16 doublets of Nb_2O_5 and SiO_2. The measurement of the mechanical losses gives a value of about $4.6\ 10^{-4}$. This value is affected by an error of 20% due to the uncertainty on the Young modulus of Nb_2O_5 which is used to deduce the coating mechanical losses from the quality factor of the coated cantilever. In conclusion the use of Nb_2O_5 does not allow to improve the performances achievable with Ti doped Ta_2O_5.

5 Discussion

In this section we compare the performances of different types of multi-layers coatings from the point of view of the mirror thermal noise. Four different types of high index materials have been considered:

Ti: Ta_2O_5, Nb_2O_5, ZrO_2 and TiO_2. These are combined with two different types of low index materials: silica (SiO_2) and alumina (Al_2O_3). In all cases the multilayer coating design is tuned to have a transmission equal to about 4 ppm. This value has been chosen to be in the range of the transmission of the end mirrors that will be used by the advanced detectors. The mirror thermal noise is calculated assuming that the mirror displacement is sensed with a laser beam having a radius of 6 cm (defined as the distance form the axis at which the electric field goes to 1/e. This is approximately the maximum beam diameter one can use on a 35 cm diameter mirror such as those that will be used in advanced detectors. Finally, the mirror thermal noise has been calculated assuming that the coating is deposited on a substrate made of silica, since this is the material that will be used both by Advanced LIGO and Advanced Virgo.

Even if in most cases the coating thermal noise due to its internal mechanical losses is the dominant thermal noise, the simulation includes also other effects such as the substrate internal losses, the thermo-elastic damping in the coating and in the substrate and thermo-refractive effect in the coating (see [19] and reference therein for a short review of all these noise sources).

The coating parameters that have been used in the simulation are reported in the table below. Many of the parameters have been taken from the literature. The complete list of references used to build Table 3 can be found in [20].

	SiO_2	Al_2O_3	$Ti:Ta_2O_5$	TiO_2	Nb_2O_5	ZrO_2
Mechanical losses	$0.5\ 10^{-4}$	$2.4\ 10^{-4}$	$2\ 10^{-4}$	$6.3\ 10^{-3}$	$4.6\ 10^{-4}$	$2.3\ 10^{-4}$
Density (kg m^{-3})	2200	3700	6425	4230	4590	6000
Thermal conductivity (W m^{-1} K^{-1})	0.5	3.3	0.6	0.45	1	1.09
Specific Heat (J K^{-1} Kg^{-1})	746	310	269	130	590	26
Expansion coefficient (K^{-1})	$0.5\ 10^{-6}$	$8.4\ 10^{-6}$	$3.6\ 10^{-6}$	$0.5\ 10^{-6}$	$5.8\ 10^{-6}$	10^{-5}
Thermo optic coefficient (K^{-1})	$8\ 10^{-6}$	$1.3\ 10^{-6}$	$14\ 10^{-6}$	$-1.8\ 10^{-4}$	$1.43\ 10^{-5}$	10^{-4}
Young modulus (GPa)	60	210	140	290	80	200
Poisson coefficient	0.17	0.22	0.28	0.28	0.2	0.27
Refraction index	1.45	1.63	2.07	2.3	2.21	2.1

Table 3. List of coating parameters used to evaluate the mirror thermal noise

Figure 4 shows the result of the simulation. As expected the coating which performs best is the combination $Ti:Ta_2O_5/SiO_2$. The combination $Nb_2O_5/SiO2_2$ gives promising results as well. This is due to the combination of two effects. First the higher index of refraction of Nb_2O_5 allows obtaining the same reflectivity with less coating material. Second the Young modulus of Nb_2O_5 [21,22] better matches the one of the silica thus reducing the overall coating Brownian noise. It should be noted that the results for the Nb_2O_5 can be improved if a higher index of refraction (corresponding to what found in the literature) than that measured at LMA is used in the simulation. The dependency over the frequency of the thermal noise calculated for the other coating reveals that the thermo-elastic effects play a non negligible role in these coatings. According to the simulation the combination TiO_2/SiO_2 gives the worst result. This is due to the larger mechanical losses of TiO_2 but also to the large thermo-elastic dissipation. It should be noted that the mechanical losses of the TiO_2 coating reported in Table 1 were measured on a coating that was produced using evaporation. A test with TiO_2 coatings produced by ion beam sputtering needs to be done.

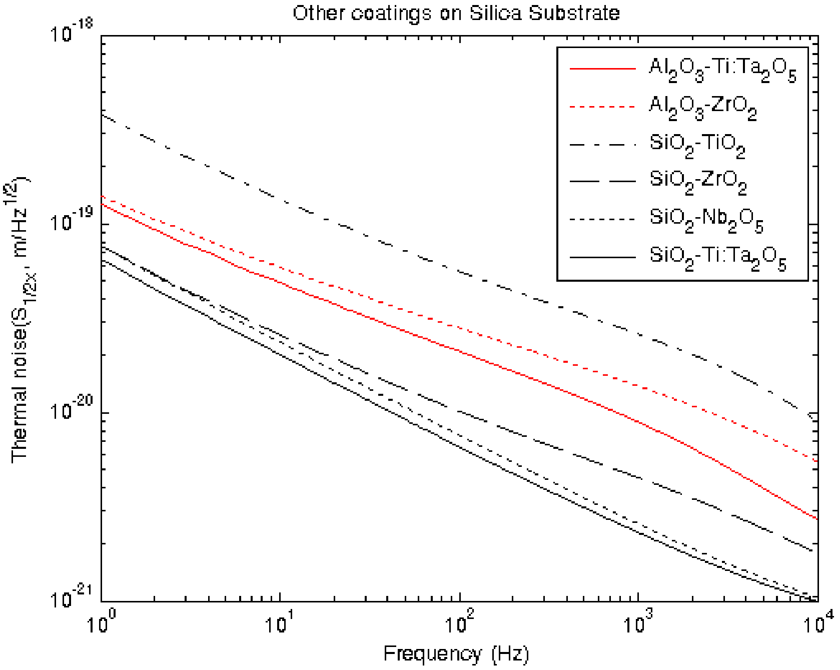

Figure 4. Mirror thermal noise expressed in m/sqrt(Hz) for different coatings deposited on fused silica substrate. The mirror displacement is readout with a beam having a size of 6 cm.

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