A study of coating mechanical and optical losses in view of reducing mirror thermal noise in gravitational wave detectors (Synopsis)

R. Flaminio, J. Franc, C. Michel, N. Morgado, L. Pinard and B. Sassolas

Synopsis by Maria Ruiz-Gonzalez

1 Introduction

This article was published in 2010 by a group from the Laboratory of Advanced Materials (*Laboratoire des Matériaux Avancés*, LMA) in France. The study was intended for the optical systems used in the Virgo Collaboration and the LIGO Scientific Collaboration (LSC), experiments whose main objective is the detection of gravitational waves. Virgo is located in Italy and LIGO in Washington and Louisiana. LIGO stands for Laser Interferometer Gravitational-Wave Observatory. In a simplified way, the primary observatory is a Michelson interferometer with 4-km Fabry-Perot cavity arms.[2, 3] If a gravitational wave passes through the interferometer, it would distort the space around it producing a length difference between the arms. Since the change in length is on the order of 10^{-18} m, all sources of noise need to be reduced as much as possible. Around a frequency of 100 Hz, one of the main sources of noise are the mirror optical coatings, as can be seen in figure 1, which produce thermal noise by absorbing light. Also, light absorption reduces optical interference. In this work, the authors test different coating materials aiming to reduce mechanical losses and optical absorption. The methods for testing optical and mechanical losses are going to be explained, as well as results for different materials.

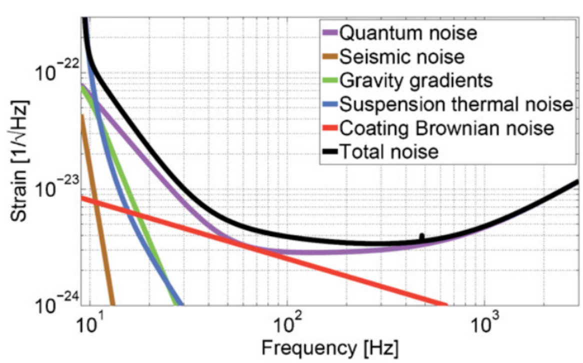

Figure 1: Different sources that contributes to noise in a gravitational-wave detector. [3]

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

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

2 Methods

For the optical loss measurements, two lasers are used. A 30 W Nd:YAG is sent to the test material and produces a thermal gradient. Then a He-Ne laser probe beam is sent through the thermal gradient, which produces a deflection in the beam. Finally, the deflection is measured and translated to coating absorption.

For the mechanical loss measurement, $45 \times 5 \times .11$ mm silica cantilevers are used. The cantilevers are coated with the test material and changes on the mechanical quality factor are measured. The fundamental, second and third resonant frequencies are 60 Hz, 400 Hz and 1.1 kHz, respectively. The uncoated cantilevers are carefully treated in order to maintain a high quality factor, on the order of 250,000. Before clamping, all surfaces are polished. Finally, the cantilever is tightly clamped. An optical lever is used to determine the cantilever position. The stress in the coating was determined by measuring the curvature of the cantilever before and after the coating was deposited.

3 Coating materials

The materials tested were Ta_2O_5, ZrO_2 and Nb_2O_2 doped with Co, W and Ti, which are oxides transparent to NIR light. Several combinations were tested.

The production of the materials was performed using a technique called ion beam sputtering, that allows to minimize impurities, which is important to reduce optical absorption.

A higher index of refraction is desirable and it is achieved by doping the material, but as can be seen in table 1, for a higher index of refraction of doped Ta_2O_5, the absorption and mechanical losses increase as well. For Ta_2O_5, the best case is obtained with Ti doping.

For ZrO_2, the results are shown in table 2. The index of refraction is higher than Ta_2O_5 and the mechanical losses are lower, but optical absorption is higher and the stress is high, which is not desired. In comparison to Ta_2O_5, ZrO_2 is not a good option.

Finally, the tests performed on Nb_2O_2 showed that the performance was not improved compared to Ta_2O_5:Ti.

4 Thermal noise

A simulation analysis was performed in which four different coating materials (Ti:Ta_2O_5, Nb_2O_5, ZrO_2 and TiO_2) were combined with silica (SiO_2) and alumina (Al_2O_3). The result for the mirror

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.

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

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

	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

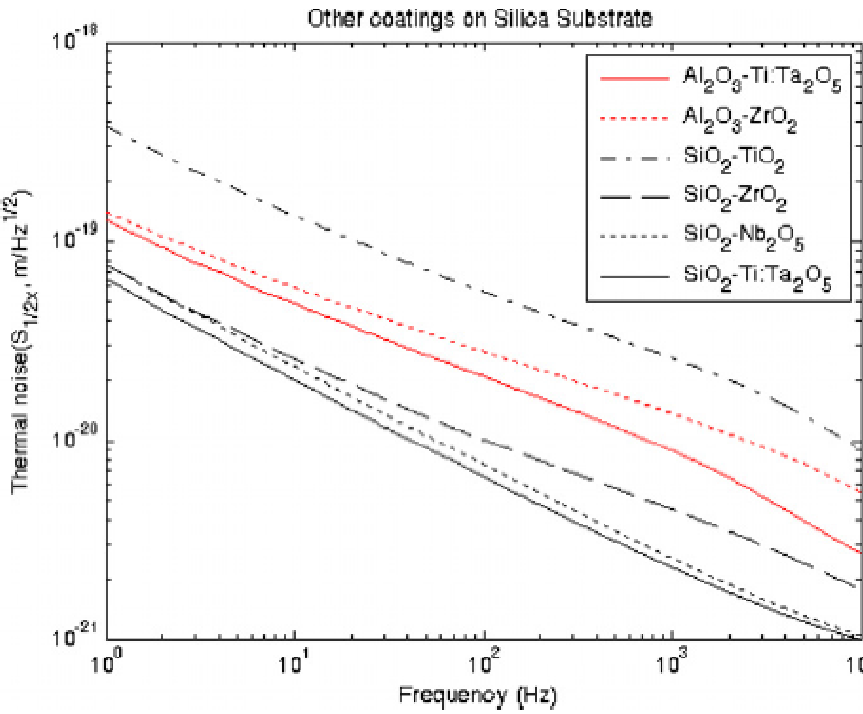

Figure 2: Mirror thermal noise for different coating materials deposited in silica and alumina.

thermal noise is shown in figure 2. The plot shows that the combination that performs best is SiO_2-Ti:Ta_2O_5, as expected. Table 3 shows the parameters used in the simulation.

5 Discussion

In this article, different materials for mirror coating are presented. Thermal noise properties were measured and compared to simulations, and it was shown that the experiment and simulation agrees. The material that performs best is SiO_2-Ti:Ta_2O_5 in the two analysis.

The work presented here is useful for a small portion of the noise spectrum, which in the gravitational-wave interferometer goes from 10 Hz to 10 kHz. Each section needs to be treated differently and this analysis presented here is a solution for the frequencies around 100 Hz.

References

[1] R. Flaminio, J. Franc, C. Michel, N. Morgado, L. Pinard and B. Sassolas; "A study of coating mechanical and optical losses in view of reducing mirror thermal noise in gravitational wave detectors," *Class. Quantum Grav* **27**, (2010).

[2] http://ligo.org/public.php

[3] Gregory M. Harry; "Advanced LIGO: the next generation of gravitational wave detectors," *Class. Quantum Grav* **27**, (2010).