Towards a new generation of low loss mirrors for the advanced gravitational waves interferometers

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Abstract : the new generation of advanced interferometer needs fused silica mirrors having better optical and mechanical properties. This paper describes the way to reduce the IBS coating absorption at 1064 nm and to improve the layer thickness uniformity in order to coat two large mirrors (diameter 35 cm) at the same time.

OCIS codes: (310.1620) Interference coatings (310.1860) Deposition and Fabrication; (310.4165) Multilayer design

1. Introduction

Several gravitational waves interferometers (VIRGO in Italy, LIGO in USA) have been running for many years and have now reached their design sensitivity. Nevertheless, a sensitivity improvement is now necessary to increase the probability of detectable astrophysical events. The Advanced detectors construction has been approved and financed: now we are talking about Advanced VIRGO (and Advanced LIGO). Many upgrades of different kinds are planned to improve these interferometers and one important part concerns the large mirrors (diameter 35 cm, thickness 10-20 cm). The mirror substrates are in ultra pure fused silica (Suprasil from Heraeus) on which a Ta_2O_5/SiO_2 IBS (Ion Beam Sputtering) multilayer is deposited [1].

The increase of the YAG laser power in the interferometers implies to reduce even more the layer absorption level to counterbalance the thermal lens created on the mirror by the laser beam (mirror surface deformation induced by the temperature increase).

Moreover, in the advanced interferometers, the two Fabry-Perot cavities (arms of Michelson interferometer) must be as identical as possible (same mirror transmission, same finesse). Even if our large IBS coater using RF ion sources is very reproducible, it is quite impossible to reach the symmetry specifications for the mirror transmission, especially for the cavity Input Mirror. The only solution found is to coat the two substrates in the same run. But, because of the mirror dimensions, there are a lot of experimental difficulties that must be overcome. Moreover, the transmission value must be uniform on each mirror on a large area.

In the following paragraphs, we describe first how we manage to decrease the mirror absorption at a level much lower than the present VIRGO mirrors [2]. Secondly, the way to improve the layers (Ta_2O_5-SiO_2) thickness uniformity on a diameter of 80 cm is detailed. This is the first and crucial step necessary to deposit a multilayer mirror on two substrates at the same time having the same spectral performances. This study was done in the framework of VIRGO + which is a VIRGO upgrade.

2. Improvement of the IBS coating absorption

More than 6 years ago, one important source of loss in the Virgo interferometer was identified to be the coating thermal noise. A lot of work has been done [3] to modify and optimize the high index layers (Ta_2O_5) which are the main source of mechanical loss (directly proportional to the Ta_2O_5 total thickness). Consequently, we have started to investigate other high index coating materials that may give lower mechanical loss while retaining the optical properties (high reflectivity, low scatter, low absorption): ternary alloys, doped materials. The best compromise found was to dope the tantalum pentoxide with Ti atoms [4]. At the beginning, we feared that the optical properties may be damaged. It was exactly the contrary: the extinction coefficient is around $4\ 10^{-8}$ at 1064 nm instead of $2\ 10^{-7}$.

Thus, we have coated for example in 2007 a scale one mirror of the Advanced LIGO interferometer (diameter 34 cm, thickness 20 cm) for an experiment called LASTI (LIGO Advanced System Test Interferometer) using Ti doped Ta_2O_5. The multilayer design is a quarter-wave stack with a low transmission (10 ppm). An absorption map at 1064 nm on 12 cm in diameter can be seen in Fig.1; the absorption measurement is based on the photothermal deflection technique.

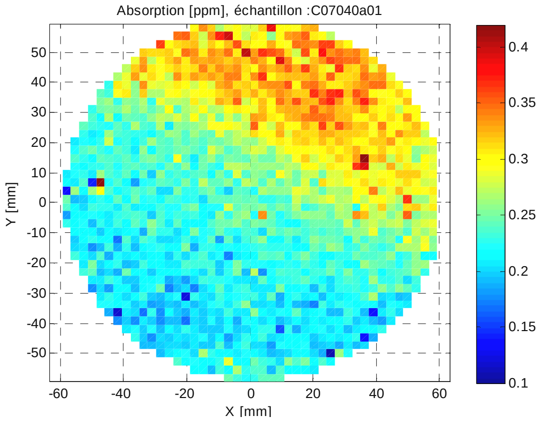

Fig.1 : Absorption map at 1064 nm on ∅12 cm of a high reflectivity mirror (average value 0.26 ppm)

The average value achieved on 12 cm in diameter is **0.26 +/- 0.05** ppm. This means that the absorption at 1064 nm is decreased by more than a factor 2 compared to the first generation of VIRGO mirrors. This low value was verified by the LIGO laboratory at Caltech and the result obtained was strictly the same.

As said before, the coating thermal noise will decrease if the high index layer total thickness decreases. In collaboration with Prof. I. Pinto (Sannio University, Italy), we have studied alternative mirror designs with non-quarter-wave layers. Nevertheless, the design is periodic (aH (bL cH)^x dL, with a,c<1 and b>1). The constraints of this design is to preserve the optical properties (transmission, absorption). The high index layers are all thinner than a $\lambda/4$ layer, but as a consequence, the low index layers are all thicker. Experimental measurements (TNI or Thermal Noise Interferometer, Caltech USA) proved that the coating mechanical losses have decreased, compared to a classical design. But, another important thing is that the mirror absorption (non quarter-wave design with Ti doped Ta_2O_5) is very low: we measured an average absorption of **0.21 ppm** at 1064 nm.

These results prove the efficiency of this non quarter-wave design, which will be probably used in the Advanced interferometers.

3. Layer thickness uniformity on large diameter

Coating thickness control is a crucial point for interference coatings. In the Advanced gravitational waves interferometers, it is required to have coatings with very good thickness uniformity in order to provide constant optical properties over the optic surface. For example, an important specification concerns the two Fabry-Perot cavities (made of one Input and one End mirror) which must have the same optical characteristics: mirror transmission, finesse. This is a very constringent requirement because it implies to coat two 35 cm silica substrates (fig.2) at the same time (twin mirrors). Indeed, it is unthinkable to get the same mirror transmission at the level required in two successive runs, even if our IBS coater (Fig.2) is reproducible.

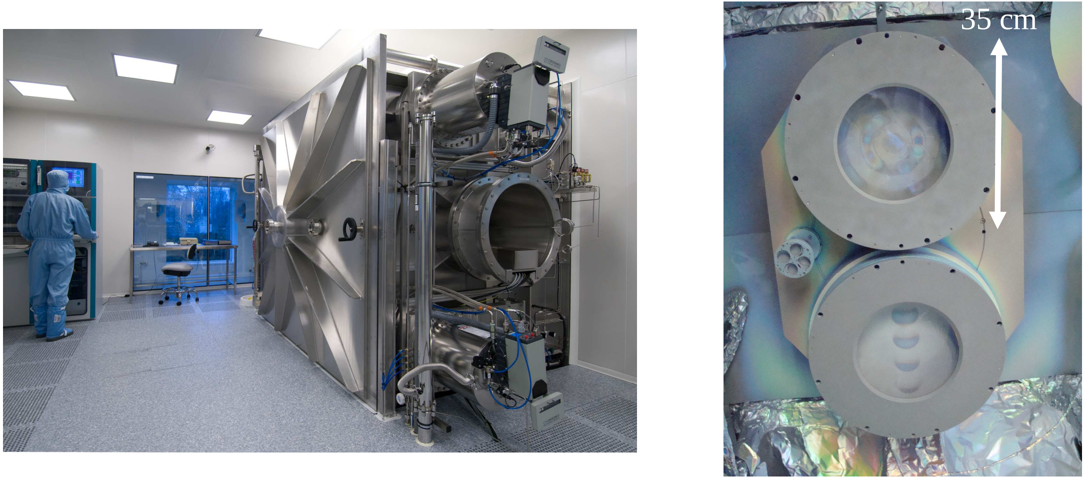

Fig.2 : Large IBS coater (left); two Virgo+ input mirrors installed on the coater sample holder before coating (right)

For the VIRGO+ interferometer, the transmission of each mirror must be **4.1%+/- 0.04%(on ∅ 12 cm central area)** and the transmission difference between the two mirrors must be also less than **0.04%**. This symmetry is more difficult to obtain on mirrors with a “high” transmission as the spectrum is not flat enough at 1064 nm; thus a small thickness error may imply a strong variation.

To reach the required layer thickness uniformity on a diameter of 80 cm, we use fixed masks between the targets and the substrates in order to control the coating thickness profiles on the rotating substrates. The mask shape is calculated with a home-made software [5]. As the sputtered particles profile is different for the high (Ti doped Ta_2O_5) and low index material (SiO_2), two different masks must be calculated, which increases even more the difficulty of the experiment.

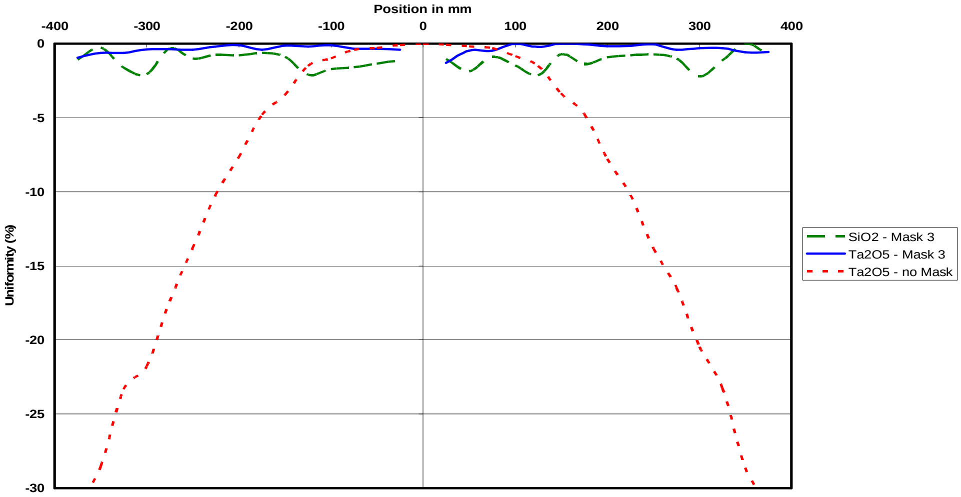

Fig.3 : Thickness uniformity with masking of SiO_2 and Ti doped Ta_2O_5 layers on 80 cm; comparison with the same uniformity without masking

To measure the thickness uniformity, we used a 80 cm long bar on which we put some microscope slides. After coating, we measure with an optical profilometer the thickness of the layers (measurement of a step).

Depending on the profile obtained, we can make an other iteration and calculate a new mask to improve the result. To get the thickness uniformity shown on Fig.3, we need three iterations.

The results obtained were satisfactory. Indeed, we get an average thickness uniformity on ∅80 cm of 0.36 % for (Ti doped Ta_2O_5) and around 1% for SiO_2, compared to the value of 30% without masking. Nevertheless, we have coated the twin Input mirrors for VIRGO+ using these uniformity values. The mirrors centers coordinates are +/- 200 mm (Fig. 3). The results are summarized in the table below

Mirror 1 Transmission (average on ∅12 cm)	Mirror 2 Transmission (average on ∅12 cm)	Transmission Difference ∅12 cm
4.126 +/- 0.014 %	**4.136 +/- 0.030 %**	**0.01 %**

The requirements are all satisfied, as well the transmission uniformity over the mirror surface as the transmission difference between the two mirrors. This is an important step we passed, as we proved that we are able to satisfy the needs for the future gravitational waves interferometer in term of coating uniformity.

4. Conclusion

Advanced gravitational waves large interferometer like VIRGO will need mirrors with improved optical performances. We have demonstrated on large optics that absorption level below 0.3 ppm at 1064 nm is perfectly realistic thanks to the development of new high index material as well as the use of optimized design. In spite of these good results, the R&D on the high index material is always going on to try to decrease even more the absorption and the mechanical losses.

Moreover, we have developed a process by using masks to realize twin mirrors (diameter 35 cm) having the same optical performances. This is the first time that such an experiment is done in an IBS coating machine on so large silica substrates.

These two results are very important because this is exactly what Advanced VIRGO and Advanced LIGO need.

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