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Different approaches to improve the wavefront of low-loss mirrors used in the VIRGO gravitational wave antenna

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Different approaches to improve the wavefront of low-loss mirrors used in the VIRGO gravitational wave antenna

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1 - Introduction

The franco-italian VIRGO program, which goal is to build a giant Michelson type interferometer (3 km arms) to detect gravitational waves, has fixed very severe optical requirements on the mirrors.

The optical losses (absorption, scattering) must be lower than 5 ppm (part per million) at 1064 nm. We have reached these requirements on **∅80 mm multilayer mirrors** deposited on Research Electro-Optics (REO) silica substrates by Dual Ion Beam Sputtering (D.I.B.S.). To reach this low absorption level (**0.5 ppm at 1064 nm**), the use of very pure targets is necessary. A severe control of the different steps of the deposition process is essential to avoid contaminations in the layers. The scattering is directly governed by the substrate polishing quality ; we are using micropolished substrates with a low microroughness (0.3 Å R.M.S. measured with a Micromap™ system) [1]. This is a necessary condition but not sufficient. An efficient cleaning process is also necessary to suppress all the particles whose diameter is larger than 0.2 μm. As all these conditions are gathered, low scattering levels in the 1 ppm range have been obtained at 1064 nm.

An other critical requirements concerns the mirrors wavefront. It must be as plane as possible to keep clean the TEM_{00} mode in the interferometer. For the larger mirror in the VIRGO interferometer (∅ 350 mm), we should reach 10 nm R.M.S. on 150 mm diameter.

In the following paragraphs, we are describing several methods we have tested to improve the wavefront. These tests have been done on ∅100 mm diameter high reflectivity mirrors (quarter-wave design $(HL)^n$ HLL with SiO_2 and Ta_2O_5 layers). This is the maximal size that can be coated in the deposition chamber. This constraint will no more exist in the following months because a 2.5 m cubic chamber is under construction to be able to coat the large VIRGO mirrors. The centering wavelength is 633 nm because we do not have at the moment an interferometer at 1064 nm (the wavefront control is done with a ZYGO Mark IV xp). Nevertheless, the methodologies to correct the wavefront are easily transposable to large size mirror at 1064 nm.

2 - Wavefront corrections

2.1 - Correction with annealing control

The D.I.B.S. layers are known to be very dense layers but also very stressed (210 MPa measured, confirmed by the publication [2]). One way to reduce the stress contribution on the wavefront deformation is to annealed the sample after the deposition. The annealing procedure must be well controlled because the multilayer may be delaminated from the substrate. The stress is compressive so that the wavefront has a dome shape if the substrate is flat.

The annealing produces a wavefront improvement larger than a factor of **3** : the wavefront on ∅90 mm diameter goes from 125 nm R.M.S. to 38 nm R.M.S.. This resulting deformation is due to two main factors. The first one is the thickness inhomogeneity of each layer (they are thicker at the center than at the edge of the mirror because of the substrate planetary motion in the deposition chamber). Thus, the centering wavelength at the edge is 15 nm lower than that at the center. The second factor is the remaining stress in the layers (25% of the total deformation). This part of the stress can be removed only if we increase the annealing temperature. But, this solution is not acceptable because the layers amorphous structure may be altered and, so, the scattering level may increase rapidly.

Thus, to improve the mirror wavefront, we have deposited a relatively thick SiO_2 layer (1 µm - 2 µm) on the back face of the mirror. This method was tested on high reflectivity mirrors which do not need antireflective coatings on the back. The mirror wavefront is modified due to the stress of the SiO_2 layer on the back side (the substrates used were only 20 mm thick) and it became a bowl instead of a dome. By annealing step by step the sample (Figure 1) and by controlling at each step the wavefront with the interferometer, we reduce gradually the stress of the SiO_2.and the annealing is stopped when the wavefront is quite plane. The result obtained is very convincing : the wavefront improvement is better than **a factor of 3 (10 nm R.M.S. instead of 38 nm R.M.S. ∅90 mm diameter).** This correction method is really simple to implement and it gives good result. But this method can only be used in particular cases when no antireflective coatings are needed on the back side.

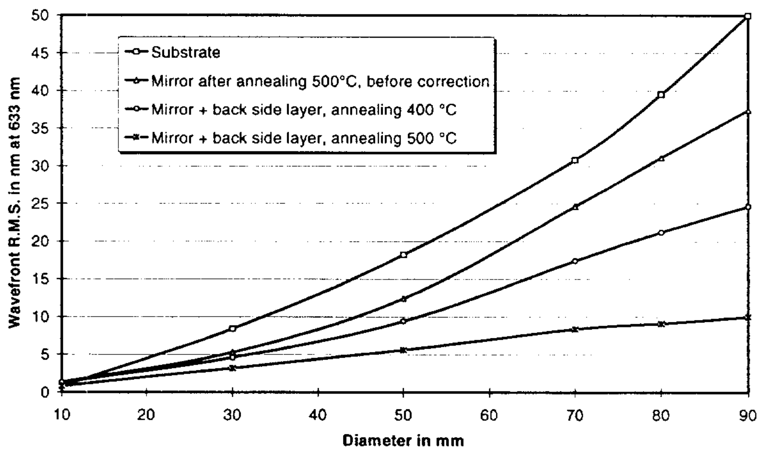

Figure 1 : Wavefront variation as a function of the annealing temperature

2.2 - Correction by using masks

A simulation program has been developed in the lab [3] to describe precisely the sputtering phenomenon in the D.I.B.S. process and to study the layer thickness uniformity. It takes into account all the geometrical and electrical parameters of the chamber so that we can obtain very realistic results. This is a real advantage of this software as we can simulate every configuration of the D.I.B.S. chamber and find the best one (best thickness uniformity of the layers).
An other option of this software is to include a fixed mask in front of the substrates during the deposition, coupled with a simple rotation of the substrate, to correct the thickness uniformity. The position in the chamber and the shape of this mask are determined by simulation. The first experimental tests presented have been done on the SiO_2 and Ta_2O_5 monolayers because the masks are not identical for both materials. So we need a system to change alternatively the masks to be able to deposit a complete mirror with the mask correction (this will be done in a near future).

Nevertheless, the results obtained, which verify the simulated values, are very promising : for a SiO_2 or Ta_2O_5 monolayer, the thickness homogeneity ($\frac{E_{max} - E_{min}}{E_{av}}$, E_{max} maximum thickness, E_{min} minimum thickness, E_{av} average thickness) goes from **$3.5.10^{-2}$ to 6.10^{-3} on ∅80 mm diameter** (decrease by a factor of **6**). If we look at Figure 1, the uniformity of **$3.5\ 10^{-2}$** for each layer leads to a wavefront deformation of 23 nm R.M.S. for a mirror (stress contribution subtracted). So, we can forsee, with the mask correction, a mirror wavefront of about 4 nm R.M.S..

2.3 - Corrective coating treatment

This third method is the most elaborated and the most powerful one. To modify the wavefront shape, a small amount of SiO_2 is deposited through a small hole (circle or square) on the last low index layer of the multilayer stack, where it is necessary. The addition of this thin SiO_2 layer (its thickness is variable) produces locally a phase retardation which is controlled with the interferometer.

Before doing the experimental tests, calculations have been done to know numerically how does the multilayer phase in reflection φ vary when the SiO_2 thickness locally increases. The starting quarter-wave design is $(HL)^n$ H and the result of this calculation are shown on the Figure 2. The variation is linear with a slope of 1 only on a small region centered around the inflection point of the curve. The width of this region corresponds to half a quarter-wave SiO_2 layer thickness (500 Å at 633 nm or 900 Å at 1064 nm). This is the maximum wavefront defect that can be corrected.

For the corrective coating to be efficient, the starting multilayer design must be **$(HL)^n$ H 0.7L** to be situated at the beginning of the linear zone. The linear variation allows a good control of the wavefront correction and the accuracy will be only limited by the interferometer accuracy.

These calculations include the random layer thickness errors and the absorption of each layers (extinction coefficient of 4.10^{-7} for both materials).

We have implemented this corrective method in the D.I.B.S. chamber. A robot, working under vacuum, was built and it is piloted by an home-made software. Every movement is possible in the X-Y plane of the sample (a 100×100 mm square can be described in this plane). The first step is the measurement of the mirror wavefront (design $(HL)^n$ H 0.7L) with the Zygo interferometer before correction and after annealing (stress relaxation). The wavefront data are used by an other home-made software to determine automatically what is the necessary silica thickness to be added at each point of the sample to improve the wavefront flatness (the deposition speed of the silica layer through the hole is measured experimentally).

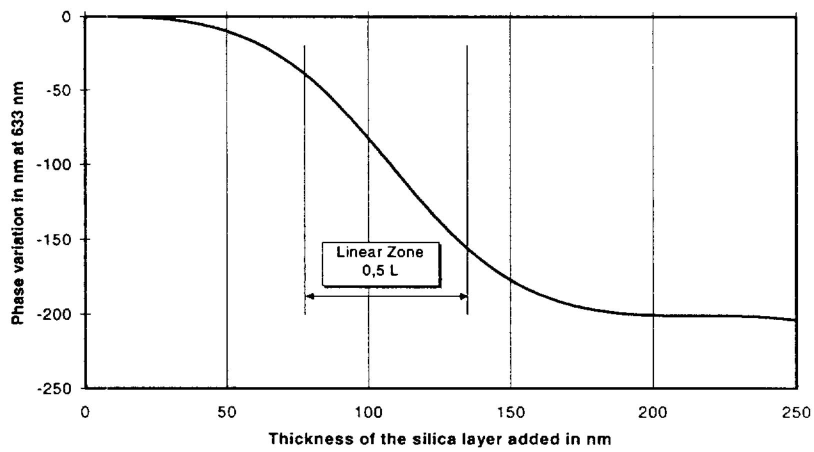

Figure 2 : Variation of the multilayer phase as a function of the SiO_2 thickness added

The software generates a file used to pilot the robot. Figure 3 shows what can be achieved with this wavefront correction.The R.M.S. wavefront goes from **6 nm to 1.5 nm** after correction on 80 mm in diameter. At this level of flatness, we are limited by the Zygo interferometer accuracy (5-10 nm peak to valley) and repeatability. The VIRGO requirements on the wavefront are satisfied on ∅100 mm mirror.

We checked that this correction method has not modified the scattering and the absorption level of the mirror. The residual transmission was deteriorated a little bit, but, by increasing the number of doublets HL, we can recover the desired transmission.

These measurements are not absolute measurements because they include the ∅100 mm reference flat of the interferometer. We have corrected the wavefront defects of the couple reference flat/mirror. Nevertheless, the feasibility of this correction method is clear and this is a very powerful method. The next development of the corrective treatment will be to suppress the reference flat contribution with the "three-flat method" for example.

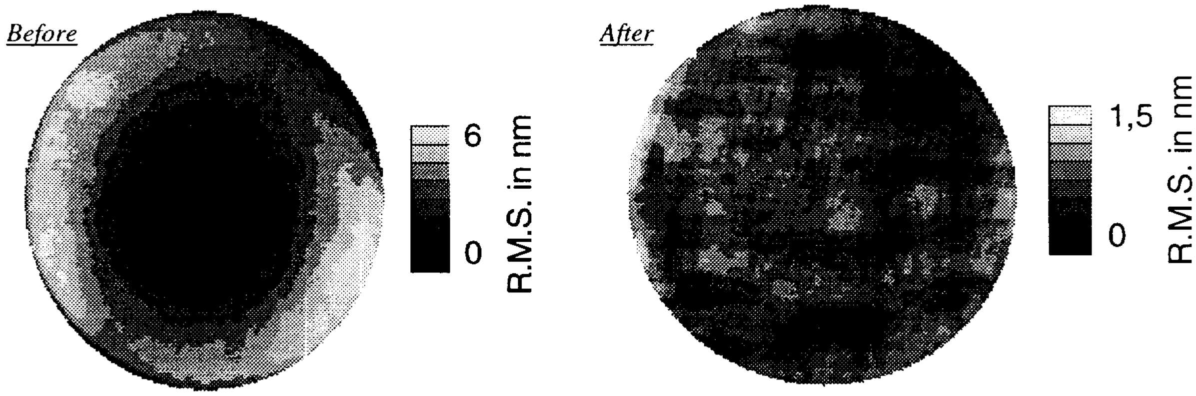

Figure 3 : Wavefront at 633 nm of a ∅100 mm mirror before and after the corrective coating

3 - Conclusion and perspectives

We have developed experimental methods to correct mirror wavefronts to achieve the very severe VIRGO requirements. The results are very convincing and the requirements have been obtained on ∅100 mm mirrors. The next step of this study will be to obtain the same performances on the large VIRGO substrates. A large coater (2.5 m cube), whose requirements has been defined with the simulation program, will be built and the wavefront correction will probably have two steps : at first a correction with the masks to rough out and afterwards the corrective coating.

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