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

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Abstract

Several experimental techniques have been developed and tested to improve the wavefront of low-loss mirrors used in the Virgo program. The most elaborated one, called 'Corrective Coating Treatment', allows us to reach an R.M.S. wavefront of 1.5 nm at 633 nm on 100 mm diameter high reflectivity mirrors. The next development will be to make the same correction at 1064 nm, wavelength of the Virgo interferometer on very large silica substrates (350 mm diameter).
1. Introduction

The franco-italian Virgo program is a collaborative effort of the CNRS in France and the INFN in Italy. The goal of this program is the construction of a giant Michelson type interferometer of 3 km arm length, aimed at detecting gravitational waves in the frequency range from 10 Hz to a few kHz. The detector is under construction in Cascina (Italy).

We are involved in this project to realize the large optics (maximum size 350 mm diameter, 200 mm thick, weight 40 kg). Such large mirrors, with very low-loss level (absorption and scattering < 5 ppm (part per million)), have never been manufactured at the present moment. So, this is a nice challenge. As the typical signal to detect is very small (optical path difference between the two arms about $10^{10}$ m), almost perfect optics are required to keep clean the TEM$_{00}$ mode in the arms. Very severe optical requirements on the mirrors absorption, scattering and wavefront have been fixed at 1064 nm:

- absorption and scattering < 5 ppm
- R.M.S. wavefront: 10 nm on 150 mm diameter.

The absorption level is measured by photothermal deflection spectroscopy. This system is able to measure absorption levels below 1 ppm. The scattering level is evaluated with a CASITM scatterometer (this is the only system in Europe) and the wavefront is measured with a Zygo interferometer Mark IV xp ($\lambda = 633$ nm).

We have reached the absorption and scattering requirements on 100 mm diameter multilayer mirrors (quarter-wave design) deposited on Research Electro-Optics silica substrates (R.E.O.) by Dual Ion Beam Sputtering (D.I.B.S.)

To reach this low absorption level, the use of very pure targets is necessary (purity of 99.99995%). 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 MicromapTM system). This is a necessary condition but not sufficient. An efficient cleaning process is also necessary to suppress 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 on one inch samples.

An other critical requirements concerns the mirrors wavefront. It must be as plane as possible. In the following paragraphs, we are describing several experimental methods we have tested to improve the wavefront flatness. These tests have been done on 100 mm diameter high reflectivity mirrors (quarter-wave design (HL)$^6$ HLL with SiO$_2$ (L) and Ta$_2$O$_5$ (H) layers). This is the maximal size that can be coated in the present deposition chamber. This constraint will no more exist in the following months because a new chamber is under construction (size 2.2*2.2*2 m) to be able to coat the large VIRGO mirrors.
The mirror centering wavelength is 633 nm which is the working wavelength of our control interferometer. 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 a publication). One solution to reduce the compressive stress contribution on the wavefront deformation is to anneal the sample after deposition. The annealing is simply done in the air. It must be nevertheless well controlled because the multilayer may be delaminated from the silica substrate (difference between the expansion coefficients of the layers and of 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..

The resulting deformation is due to two main factors.

At first, the thickness of each high or low index layer is not uniform (thicker at the center than at the edge). This is due to the substrate planetary motion in the deposition chamber. Thus, the centering wavelength of the mirror 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 (> 500 °C). But, this solution is not acceptable because the layers amorphous structure may be altered and the scattering level may increase rapidly.

To improve the mirror wavefront, we have deposited a relatively thick SiO₂ layer (1 - 2 μm) on the back face of the substrate. This method was tested on high reflectivity mirrors which do not need antireflective coatings on the back.

The mirror wavefront (front face) is modified due to the stress of the SiO₂ layer on the back side (the substrates used were 20 mm thick) and it became a bowl instead of a dome (Fig.1). The SiO₂ layer thickness is adjusted so that the wavefront becomes a bowl.

By annealing step by step the sample (we increase the temperature gradually) and by controlling at each step the wavefront with the interferometer, we relax gradually the stress of the SiO₂ layer. The wavefront deformation of the front face becomes less and less important.
Fig. 1: Effect of the silica layer deposited on the substrate back face on a 100 mm diameter mirror wavefront

The annealing is stopped when the wavefront is quite plane (Fig. 2). The result obtained is very convincing: the wavefront goes from 38 nm R.M.S. to 10 nm R.M.S. on 90 mm diameter.

Fig. 2: Wavefront variation due to the back side correction as a function of the annealing temperature
This correction method is really simple to implement and it gives good result. But, the correction is global and we are limited rapidly to obtain a wavefront lower than 10 nm.

2.2. Correction using masks

A simulation program has been developed in the lab 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 (chamber size, position of the sources in the chamber) and electrical parameters (intensity, voltage of the ion beams) of the deposition 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$_2$O$_5$ monolayers. For these two materials, the mask shape is different. So, to be able to deposit a multilayer mirror, we have to put in the deposition chamber a system which changes alternatively the masks. This will be done in a near future.

Nevertheless, the results obtained, which verify the simulated values, are very promising (Fig. 3) : the SiO$_2$ thickness uniformity, measured by ellipsometry ($E_{\text{av}}$, $E_{\text{max}}$, $E_{\text{min}}$ maximum thickness, minimum thickness, average thickness) goes from $3.5 \times 10^{-2}$ to $6 \times 10^{-3}$ on 80 mm diameter. With this measurement method, we do not take into account the layer stress. After the mask correction, the layer uniformity is good: the average thickness is about 1100 Å and the standard deviation is about 1 Å.
Although we do not have deposit a complete multilayer mirror with this technique, we can make an estimation of the global wavefront deformation taking into account the uniformity obtained on monolayers.

If we look at Fig. 2, a uniformity of $3.5 \times 10^{-3}$ (without correction) for each layer leads to a wavefront deformation of 22 nm R.M.S. for a mirror (stress contribution subtracted, without correction). So, we can foresee, with the mask correction, a mirror wavefront of about 4 nm R.M.S. (or 5 nm R.M.S. with the stress contribution) which corresponds to a thickness uniformity of each monolayer of $6 \times 10^{-3}$. This value will be checked rapidly by depositing a complete mirror on a 100 mm diameter silica substrate.

2.3 - Corrective coating treatment

This third method is the most elaborated and the most powerful one. The purpose of the corrective coating is to improve the mirror wavefront shape by depositing directly on the last low index layer of the mirror a small amount of SiO$_2$ (same material as the mirror last layer) through a small mask (circle or square), only where it is necessary. The addition of this thin SiO$_2$ layer (its thickness is variable) produces locally a phase retardation which is controlled by interferometry.

Before doing the experimental tests, calculations have been done to know numerically how does the multilayer phase in reflection $\varphi$ vary when the SiO$_2$ thickness locally increases. The starting quarter-wave design is (HL)$^n$ H and the result of this calculation is shown on Fig.4.

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 (50 nm at 633 nm or 90 nm at 1064 nm). This is the maximum wavefront defect that can be corrected.
Fig. 4: Variation of the mirror phase as a function of the SiO₂ thickness added

For the corrective coating to be efficient, the starting multilayer design must be (HL)⁶ 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: 5 \times 10^{-7} for both materials).

To realize the corrective coating treatment experimentally, a robot, working under vacuum, was built in the D.I.B.S. chamber. An home-made software was developed to pilot this robot and to allow every movement in the X-Y plane of the sample. Thus, a 100x100 mm square can be described in this plane.

To determine where we must add some silica, the first step is to measure the mirror wavefront (design (HL)⁶H 0.7L) before correction and after annealing (compressive stress relaxation) with the Zygo interferometer. The stress (500°C, ambient atmosphere) is reduced by a factor 4 with the annealing. The wavefront data are used by an other home-made software to determine 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 mask is measured experimentally). The software generates a file used to pilot the robot. Thus, the corrective coating treatment can start.

Fig. 5 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 a 100 mm diameter mirror. At this level of flatness, we are limited by the Zygo interferometer accuracy and repeatability. The Virgo requirements on the wavefront are satisfied on a 100 mm diameter mirror.
Fig. 5: Wavefront at 633 nm of a 100 mm diameter mirror before and after the corrective coating (clear aperture 80 mm)

We checked that this correction method has not modified the scattering and the absorption level of the mirror which is a fundamental point. The residual transmission was deteriorated because the multilayer design after the correction is no more a standard quarter-wave design. But, by depositing one or two more doublets HL, we can recover the desired transmission.

These measurements are not absolute measurements because they include the 100 mm diameter 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”\(^7\).\(^8\)

3 - Conclusion and perspectives

We have developed experimental methods to correct mirror wavefronts to reach the very severe Virgo requirements. The correction with the annealing control is the simplest method but its performance is rapidly limited because this is a global correction.
The wavefront requirements have been obtained on 100 mm diameter mirrors with the corrective coating method at 633 nm. The next step of this study will be to obtain the same performances on the large Virgo substrates (350 mm diameter) at 1064 nm. To do so, a large coater (2.2*2.2*2 m) and a large robot are under construction and they will be delivered by the end of 1998 and a control interferometer at 1064 nm will be purchased.

The wavefront correction will probably have two steps. At first, a correction with the masks will be done to rough out. The goal is to obtain a wavefront deformation lower than 90 nm at 1064 nm for the corrective coating to be efficient. Secondly, the corrective coating treatment will be done. Normally, no technical problems should occur because we only have to scale this method to the large samples. It will just be a question of time (we have estimated the time to make the wavefront correction of a large mirror to about 100 hours).

References

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