Mirrors used in the LIGO interferometers for first detection of gravitational waves

L Pinard, C Michel, B Sassolas, L Balzarini, J Degallaix, V Dolique, R Flaminio, D Forest, M Granata, B Lagrange, et al.

The mirrors used in the LIGO interferometers for the first detection of gravitational waves

L. PINARD[1,*], C. MICHEL[1], B. SASSOLAS[1], L. BALZARINI[1,2], J. DEGALLAIX[1], V. DOLIQUE[1], R. FLAMINIO[3], D. FOREST[1], M. GRANATA[1],B. LAGRANGE[1], N. STRANIERO, J. TEILLON[1], G. CAGNOLI[1,2]

[1]*Laboratoire des Matériaux Avancés - CNRS/IN2P3 – F-69622 – Villeurbanne France*
[2]*Université Claude Bernard Lyon 1 – F-69622 – Villeurbanne France*
[3]*National Astronomical Observatory of Japan, 181-8588 Tokyo, Japan*
**Corresponding author: l.pinard@lma.in2p3.fr*

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXX

For the first time, a direct detection of gravitational wave occurred in the LIGO interferometers. These advanced detectors need large fused silica mirrors having optical and mechanical properties never reached up to now. This paper details the main achievements of these IBS coatings.

OCIS codes: *(310.1620) Interference coatings, (310.1860) Deposition and Fabrication; (310.4165) Multilayer design, (310.6860) Thin films, optical properties*

http://dx.doi.org/10.1364/AO.99.099999

1. INTRODUCTION

On September 14, 2015 at 09:50:45 UTC, the two detectors of the Laser Interferometer Gravitational wave Observatory (LIGO) simultaneously observed a transient gravitational-wave signal [1]. The signal matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

The Laboratoire des Matériaux Avancés (LMA) was in charge of providing the coatings for more than 30 large optics (34/35 cm up to 55 cm diameter and 20 cm thick) for Advanced LIGO and Advanced Virgo gravitational wave interferometers.
In particular, LMA has coated the 20 arm cavity mirrors (Input Mirror (IM) and End Mirrors (EM)) of Advanced LIGO and all the mirrors of Advanced Virgo. Furthermore, we have coated the large Advanced Virgo Beam Splitter (**Ø55 cm**, 6.5 cm in Thickness) which is the largest optical part ever coated by Ion Beam Sputtering IBS) (Fig 1).

The mirror substrates are made in ultra-pure fused silica (Suprasil from Heraeus Quartz Glass) on which a Ti-Ta_2O_5/SiO_2 IBS multilayers is deposited [2]. The increased YAG input laser power in the interferometers implies also to reduce even further the optical absorption of the coating down to sub-ppm level to limit thermal lensing effects (mirror surface deformation induced by the temperature increase).

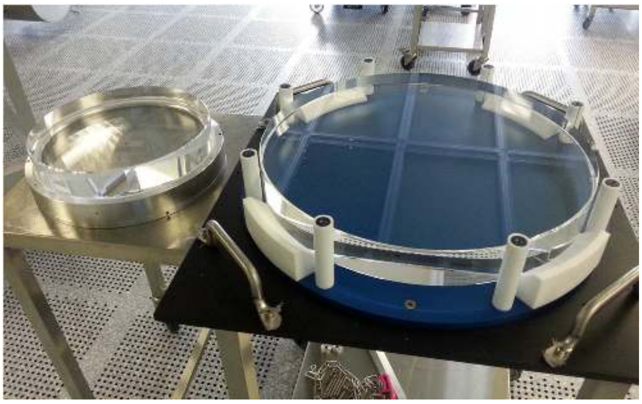

Fig. 1: Advanced Virgo recycling mirror Ø35 cm (left) and large Beam Splitter Ø55 cm (right)

Moreover, in the advanced detectors, the two Fabry-Perot cavities (arms of the 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 almost impossible to reach the symmetry specifications for the High Reflective (HR) coating transmission, especially for the Input Mirrors (Transmission of 1.4+/- 0.1% at 1064 nm with ΔT<0.01%). The only solution is to coat the two substrates in the same run using a planetary motion. In addition, the transmission value must be uniform on each mirror on a large area implying a strong improvement of the coating uniformity on a large scale (better than 0.1% over 15 cm diameter). This last requirement is particularly difficult for the HR coating of the EM whose total thickness is close to 6μm.

In the following sections, after having detailed the silica substrate and the coating specifications, we describe how we managed to improve the mirror absorption and the scattering at a level much lower than the first generation of VIRGO mirrors [3]. Secondly, the way to improve the multilayers (Ti-Ta_2O_5/SiO_2) thickness uniformity on a large diameter is detailed.

2. SILICA SUBSTRATES AND COATING SPECIFICATIONS

As an example, the substrates (Ø35 cm, 20 cm thick) chosen for the Advanced Virgo Fabry-Perot cavities mirrors are made of ultra-pure fused silica. It was decided to use the last generation of Suprasil developed by Heraeus (Suprasil 3002) as bulk material for the IM. This choice is mainly driven by the high homogeneity of the refractive index and the extremely low bulk absorption at 1064 nm: **0.2 ppm/cm** (part per million). For the EM, crossed by only a small amount of light, the constraints are less stringent and Suprasil 312 was chosen.

Very severe polishing specifications were defined in order to guarantee after coating a low scattering level as well as extremely good flatness (Fig. 2). Indeed, here are below the most stringent specifications asked to the polishing company:

- Microroughness < 1 Angström RMS
- Flatness < 0.5 nm RMS on the central Ø15 cm (low spatial frequencies < $1mm^{-1}$)
- Point defects : density < 1/4 mm^2 in Ø15 cm (defects< 5μm), <15 in Ø15 cm (defects [5μm, 50μm])

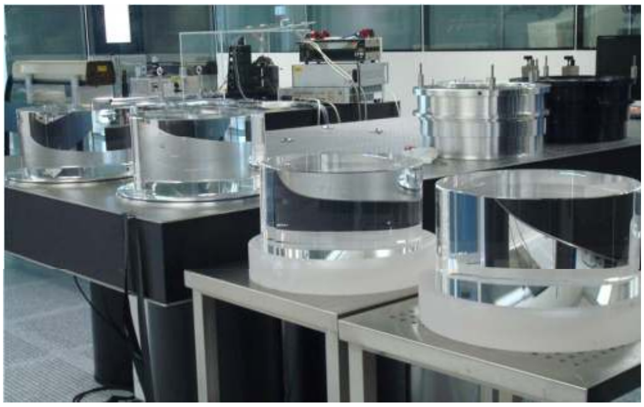

Fig. 2: Four Advanced LIGO ITM substrates before coating

On Fig. 3, a map of the point defects (Micromap profilometer measurement) and a map of the flatness (Fig. 4) on an EM substrate are shown. The optical performances of these substrates are remarkable and better than expected. The measured microroughness is around 0.6 Angström RMS.

Regarding the IBS high reflective coating specifications on the IM and EM, ultimate performances in term of absorption, scattering, flatness are required:

- Flatness after HR coating: < 0.5 nm RMS on Ø15 cm (low spatial frequencies < $1mm^{-1}$) with all Zernike terms <0.5 nm in amplitude
- Round Trip Losses lower than 50 ppm
- Average absorption at 1064 nm < 0.5 ppm (part per million)
- Average scattering at 1064 nm < 10 ppm
- HR transmission matching for IM at 1064 nm: ΔT< 0.01% with T=1.4+/- 0.1%
- 3 bands (532, 800, 1064 nm) AR coating : R<100 ppm at 1064 nm (backside of the mirror)

In addition, a low mechanical dissipation of coating is needed to minimize thermal noise.

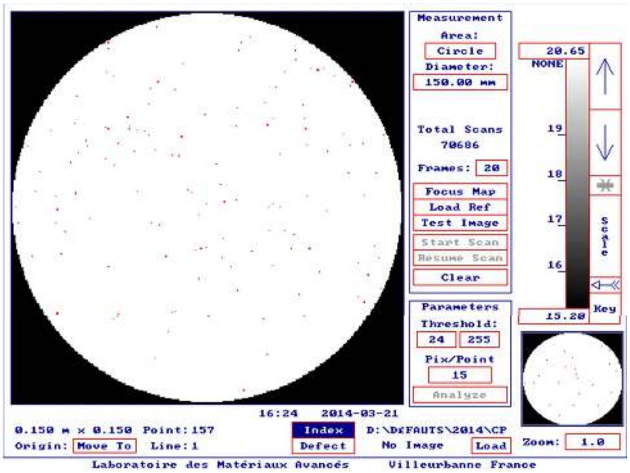

Fig. 3: Point defect map Ø15 cm of an Advanced Virgo EM

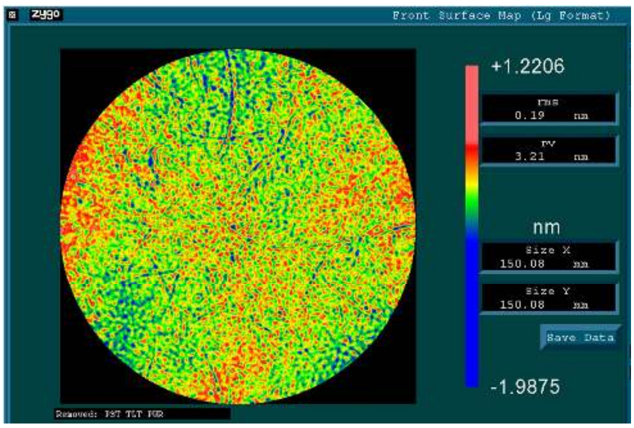

Fig. 4: Surface flatness (**0.19 nm RMS Ø15 cm**) of an Advanced Virgo EM

3. THE ADVANCED VIRGO AND ADVANCED LIGO INPUT AND END MIRRORS

A. Thermal noise and absorption

Ten years ago, one important source of noise in the Virgo interferometer was identified to be the coating thermal noise. A lot of work has been done so far [5] 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). The best compromise found was to dope Ta2O5 with Ti atoms.

In order to decrease the high index layer total thickness while keeping the mirror properties, alternative mirror coating designs with non-quarter-wave layers (aH (bL cH)x dL, with a,c<1 and b>1) have been studied [2]. Experimental measurements (TNI or Thermal Noise Interferometer, Caltech USA) proved that the coating mechanical losses decreased [7], compared to a classical design and that the average absorption at 1064 nm is also lower (from our measurements based on the photothermal deflection technique). We applied this recipe to develop the high reflective coating on the IM and EM of Advanced Virgo.

Fig. 5 shows an absorption map realized on an EM HR coating whose transmission is 3 ppm at 1064 nm. The result is remarkable: average value **0.24 ppm on Ø15 cm** at 1064 nm.

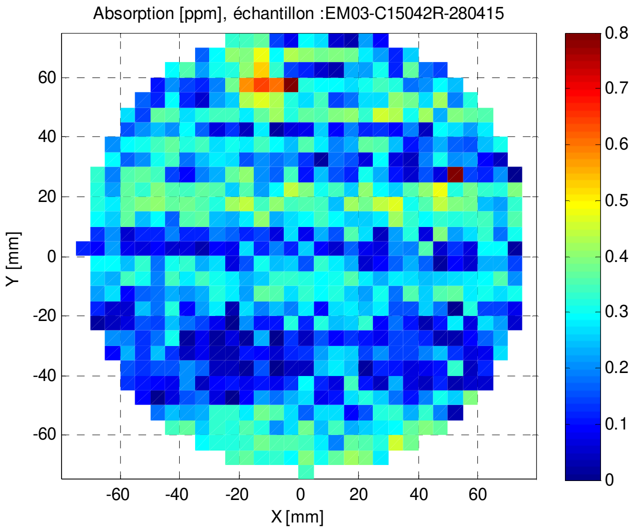

Fig. 5: Absorption map at 1064 nm on Ø15 cm of a high reflectivity coating of an EM of Advanced Virgo

For the 20 Advanced LIGO test masses coated, here is below the average absorption on Ø15 cm obtained for the two kinds of HR coating (Input mirrors, End mirrors):

- On the 10 ITMs : 0.22 +/- 0.03 ppm (average +/- σ)
- On the 10 ETMs : 0.27 +/- 0.07 ppm

B. Scattering

To improve the average scattering level after coating, a new wet cleaning machine was developed which allows us to have a better cleaning efficiency on the very small particles.

Moreover, a new procedure was put in place to control of the substrate surface just before closing the coating chamber door (visual observation in the dark with a high power halogen lamp, use of ionized dry air gun).

For the 20 Advanced LIGO test masses coated, here is below the average scattering on Ø15 cm at 1064 nm obtained for the two kinds of HR coating (Input mirrors, End mirrors):

- On 10 ITMs : 3.7 +/- 1.2 ppm
- On 10 ETMs : 4.9 +/- 1.5 ppm
- Best result : 2.3 ppm (Fig. 6)

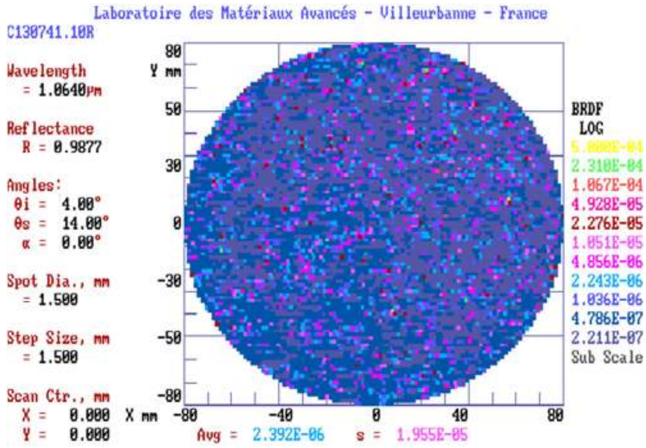

Fig. 6: Average scattering map Ø15 cm on a ITM of Advanced LIGO measured with a CASI scatterometer

C. Antireflective coating

We developed a specific three band antireflective coating (532, 800 and 1064 nm) based on a 16 layers design necessary for the Advanced Virgo interferometer.

Due to the stringent specification at 1064 nm (R<100 ppm with a goal of 50 ppm), we tried to find during the design optimization a solution for this wavelength as less sensitive as possible to manufacturing errors. We have done 1000 situations to test the robustness of the design by applying a random error of +/-1% on all layers. On Fig 7, we can see the worst trial and the higher reflectivity value we can have is 100 ppm.

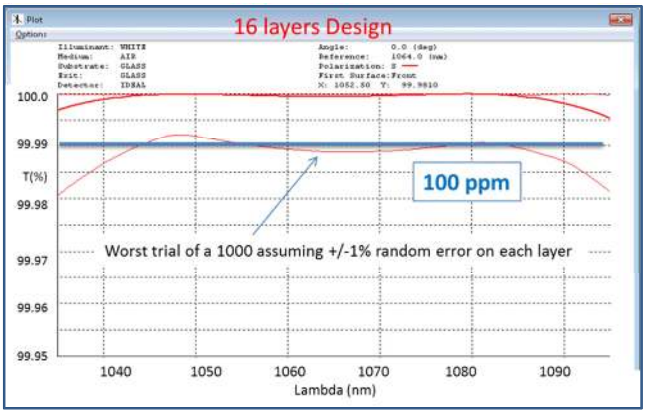

Fig. 7: Zoom of the AR spectrum around 1064 nm with sensitivity to errors (of random manufacturing errors +/-1% on all layers)

The design found has shown experimentally a remarkable robustness to errors. Indeed, 100% of AR coatings made on large optics using this design on more than 20 large substrates have a reflectivity lower than 100 ppm, 80% less than 50 ppm. An example of achievement can be seen on Fig. 8: **13 ppm +/- 6 ppm on Ø15 cm.**

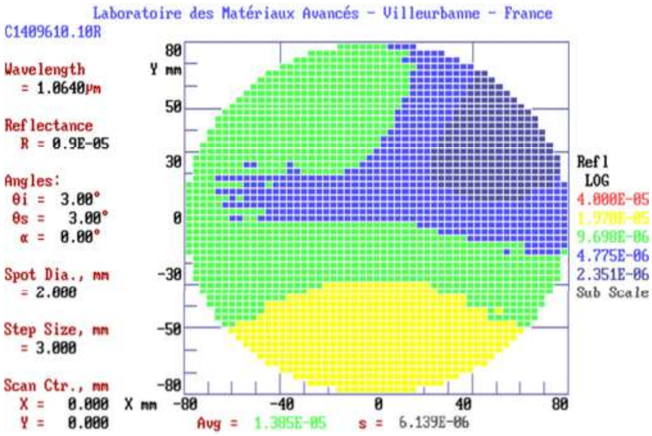

Fig. 8: Reflexion map at 1064 nm on Ø16 cm of an AR coating of an ITM of Advanced LIGO (average value 13 ppm)

D. Mirror Flatness

For the first generation of Virgo mirrors made in 2002 and 2009, a large IBS (Ion Beam Sputtering) coating chamber was developed at LMA (Fig. 9). The coating thickness uniformity needed was not so stringent: indeed the mirror flatness should be lower than 3 nm RMS on Ø15 cm. For the Advanced detector, the flatness must be better than 0.5 nm RMS over the same diameter: this is a huge difference.

Images LMA Photothèque CNRS 2008 - Hubert Raguet

Fig. 9: Large IBS coater

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 optics surface. Two Fabry-Perot cavities (made of one Input and one End mirror) must have the same optical characteristics: mirror transmission, finesse, round trip losses. It implies to coat two 35 cm silica substrates (Fig. 9) 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 is very reproducible.

To reach the flatness requirement after coating on the Advanced LIGO and Advanced Virgo large mirrors, we developed at LMA a new sample holder with a planetary motion coupled with dedicated masks (between the targets and the substrates).

Fig. 10: Two Ø35 cm IM installed in the coater sample holder

For each material, a mask shape is calculated with an home-made simulation software because the sputtered particles profiles are different. Thus, we are able to coat two 40 kg mirrors in the same run (Fig. 10).

The mask shape optimization was made first on monolayer deposited on large fused silica plates (Ø35 cm, 6 mm thick) with spectrophotometric measurements along diameters.

Some limitations linked to the metrology device were rapidly observed when the uniformity level became lower than 0.2% on Ø16 cm (unable to well optimize the mask shape, uncertainties).

So we decided to measure the coating uniformity directly on the HR coatings. The uniformity profiles are deducted from reflectivity measurements at large AOI on the edge of the reflectivity band of the multilayer using a CASI scatterometer. The reflectivity variation are converted in centering variation and then in thickness variation.

Fig. 11 shows the average uniformity profile obtained on Ø24 cm for a HR coating of an EM (6µn total thickness). The uniformity reached is remarkable: **#0.05% on Ø20 cm** or 3 nm PV for a HR coating of an EM.

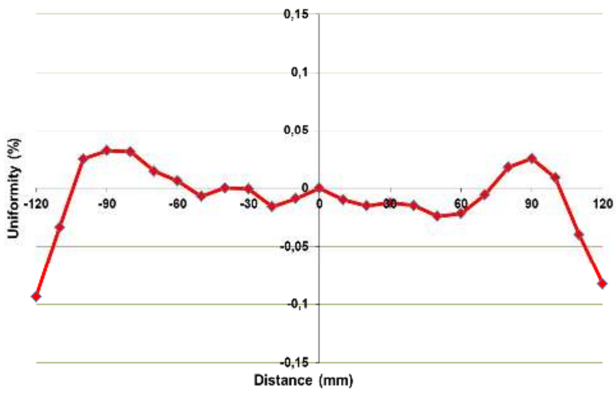

Fig. 11: Average uniformity profile on Ø24 cm of an EM high reflective coating

Fig. 12 shows the flatness achieved on a HR coating of an Advanced Virgo EM (total thickness 6 µm) which satisfies the requirement: **0.37 nm RMS on Ø15 cm**.

The transmission matching of the two IM and the two EM was also a success (average transmission difference between the two IM is 0.002%).

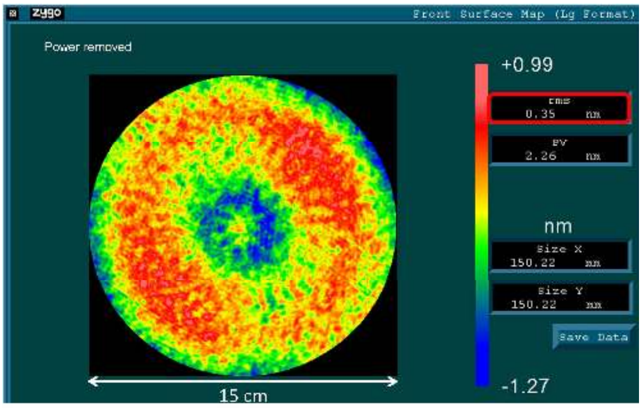

Fig. 12: Flatness of an Advanced Virgo EM on Ø15 cm (Power removed)

4. CONCLUSION

LMA was able to reach the required specifications for the arm cavity mirrors of the advanced gravitational wave detectors. This is the first time such performances on coating uniformity, absorption, scattering were achieved on 35 cm mirrors made by IBS.

We can in any case say that the first detected gravitational wave (and the future ones….) has passed between two large mirrors coated at LMA.

References

1. B. P. Abbott et al., "Observation of Gravitational Waves from a Binary Black Hole Merger", Physical Review Letters, 116, 061102 (2016).
2. L. Pinard, B. Sassolas, R. Flaminio, D. Forest, A. Lacoudre, C. Michel, J.L. Montorio, N. Morgado, Optics Letters, "Toward a new generation of low-loss mirrors for the advanced gravitational waves interferometers", Optics Letter vol. 36 n°8 (2011) 1407
3. B. Cimma, D. Forest, P. Ganau, B. Lagrange, J.M. Mackowski, C. Michel, J.L. Montorio, N. Morgado, R. Pignard, L. Pinard, A.Remillieux, "IBS sputtering coatings on large substrates: towards an improvement of the mechanical and optical performances", Applied Optics, vol. 45 n°7 (2006) 1436-1439
4. R. Bonnand – "The Advanced Virgo gravitational waves detector : Study of the optical design and development of the mirrors" – PhD : https://tel.archives-ouvertes.fr/tel-00980687
5. M. Granata, E. Saracco, N. Morgado, A. Cajgfinger, G. Cagnoli, J. Degallaix, V. Dolique, D. Forest, J. Franc, C. Michel, L. Pinard, R. Flaminio, "Mechanical loss in state-of-the-art amorphous optical coatings", Physical Review D 93, 012007 (2016)
6. B. Sassolas, R. Flaminio, J. Franc, C. Michel, J.L. Montorio, N. Morgado, L. Pinard, "Masking technique for coating thickness control on large and strongly aspherical optics", Applied Optics, vol.48 n°19 (2009) 3760
7. A. E. Villar et al., Measurement of thermal noise in multilayer coatings with optimized layer thickness, Phys. Rev. D 81, 122001 (2010)