Nanolayered Reflective Coatings for Interferometric Gravitational Wave Detectors


LIGO-G1901127
Gravitational waves (GW) are emitted when two massive bodies (like black holes or neutron stars) orbit each other until they eventually inspiral and collide. These are among the most massive objects in the universe, yet the GW they emit are incredibly difficult to detect.

LIGO (the Laser Interferometer Gravitational-Wave Observatory) and Virgo were created to detect these waves using some of the most advanced measuring techniques ever created. They will be joined by other detectors in the future.
How LIGO Works

Ground-based interferometric detectors use high-powered coherent light which is split into two orthogonal, km-scale Fabry Perot cavities and then recombined. By tuning the arms, the beams can recombine in such a way that they mostly cancel each other out. When a GW comes, it differentially moves the FP mirrors and modulates the light output.

When noise sources are controlled for, a GW signal can be detected. Using the times that the signals were observed at the different interferometers, it is possible to triangulate the position of the GW source.
Limiting the noise in the detectors is a critical step for these interferometers. Currently, the most sensitive detection band of frequencies is around 100 Hz. In this region, noise induced by the interferometers’ mirrors is the dominant noise. Reducing this noise is an urgent priority.
Scattered Light

- Stored standing power in Fabry Perot cavities is on the order of a megawatt
- Tens of ppm of stored light (tens of watts!) are scattered at large angles, and some fraction comes back and reenters the beam with random phase, spoiling the sensitivity

Thermal Noise

- Thermal noise occurs when dissipation dumps mechanical oscillation energy into the thermal bath
- Millions of femto scatterers have been observed, and are believed to contribute to the increased dissipation in coatings

Double opportunity for improvement
Slow Deposition on Warm Substrates

• More time for ad-atoms to relax and reduce number and size of voids
• Positive results are washed out by annealing process which is applied to perfect stoichiometry of the glass oxide (necessary to reduce power absorption) and improve the quality factor of the deposited glass more than the slow-warm deposition

Nanolayering (this presentation)

• Different materials within the ~1/4 wavelength coating layers are nano-layered to suppress the formation of crystallites
• Based on the assumption that the observed scatterers are crystallites, i.e. the germs from which crystalline growth starts, we expect:
  • higher crystallization temperature
  • lower dissipation/ thermal noise
  • less scattering
• Crystallites form because the crystal is the state with lowest energy.

• Because the volume grows with the cube of the size while the surface only with the square, eventually the gain wins, but only if the critical size at which the two cost equal is reached. Below that critical size, crystallites tend to melt into a glass.

• A way to suppress crystallite formation is to alternate nanolayers of different materials that are thinner than the crystallite critical size in a given oxide.

Crystallites
The experience of the X-ray mirror community suggests that crystallite suppression should happen at a few nm level.

Recent measurements by Kuo et. al. (LIGO-G1900356) showed that titania’s crystallization temperature shoots up from 2-300 °C in thicker films to 7-800 °C when silica and titania are nano-layered below 2 nm. One can be reasonably sure that the change in crystallization threshold is due to titania, because the glassy transition in silica is known to be much higher.
Coating Production

The laboratory at the University of Sannio is equipped with an OptoTech OAC 75-F coater with an electron-beam gun to thermally evaporate atoms from multiple targets while using ion-bombardment to increase the density and uniformity of the dielectric coatings. The machine can create nanolayered coatings with many different recipes in order to find the optimal mirrors.
Characterization 1: XRD

X-Ray Diffraction

• Identify the crystallization threshold temperature by observing the appearance of crystal peaks
• At sufficiently high temperature, the increased atomic mobility allows rapid growth of crystallites
• At 3.2 nm, crystallization is pushed above 450 °C

8 Layers TiO2-ZrO2
25.6 nm layers, 200 nm total

64 Layers TiO2-ZrO2
3.2 nm layers, 200 nm total
Characterization 2: AFM

Atomic Force Microscopy

- Surface roughness measurements indicate the efficiency of the coater
- Larger roughness for thicker layers may indicate the presence of crystallites
- Higher smoothness for thin layers (on the order of ~1 nm) may indicate suppression of crystallite formation

SiO2-TiO2
128 nm total
Microscope Analysis

- Crystallites have higher density, higher index of refraction, and scatter light. Even a small intensity focused by the microscope lens onto a small area results in a power density competing with that stored in a GW FP.
- Depth of each scatterer can be determined with a resolution smaller than the $\frac{1}{4}$ wavelength of a layer.

Scatterer moving in and out of focus during scan
~15 steps between each

64 Layers TiO$_2$-ZrO$_2$
200 nm total