Research Project

New approaches in coating R&D for future gravitational wave detectors

Research Area

The project presented here involves physics topics from FIS/01 (Experimental physics) and FIS/03 (Physics of matter).

State of the art

One of the most promising areas of research in modern physics is devoted to detecting and studying Gravitational Waves (GW), opening up new channels for observing astrophysical events from celestial bodies of large and compact mass. Considerable efforts are focused on new materials and technological advances for the interferometric detectors (ITF) designed for such purposes.

Considering the intensity of the signal characterizing the GWs, their detection is one of the most challenging measurements of recent years. To reach a satisfactory level of noise reduction, many noise sources have been tackled, and novel devices and techniques have been developed, in an effort to improve the sensitivity of the ITFs.

As of today, Thermal Noise (TN) is one of the most important noise sources that limit the sensitivity of the GW detectors currently operational, and it will become even more crucial for the next generation of detectors. TN in the multi-layer reflecting coating of the suspended mirrors is the dominant source of noise in the mid-range frequency band (10-100 Hz) [1], the observational band with the higher Signal-to-Noise Ratio. The research activity in coatings in GW detectors has led to High Reflecting (HR) Bragg stacks, made of alternate layers of silica and tantalum pentoxide doped with titanium dioxide, deposited at Laboratoire des Matériaux Avancés (LMA). Very low optical absorption (~ ppm) and spectacular uniformity over large diameters (up to 35 cm) are key features of these stacks. Nonetheless, a high level of thermal noise is still present, so the research laboratories that lead the large GW detector collaborations worldwide (LIGO, Virgo, KAGRA) started projects to study and reduce coating losses, within the vision of the future generation GW detectors (Einstein Telescope (ET)).

ET will be a large underground and cryogenic interferometer, designed to improve the sensitivity by a factor of 10 compared to the current generation of interferometers [2]. It will consist of one interferometer devoted to the detection of the low-frequency components (ET-LF) of the GW spectrum ([2-40] Hz), and a second one dedicated to the high-frequency components (ET-HF), each interferometer adopting different technologies and operating in different regimes: ET-HF at room temperature, whereas ET-LF at cryogenic temperature. The optical, thermal, and mechanical properties of materials for the optical components must be independently optimized for each of the two regimes.

The validation of new coating materials operating both at room and cryogenic temperature is a complicated process, involving the definition of selection criteria, technological aspects, feasibility issues, and experimental study [3]. Specific figures of merit have been identified to enforce the selection and validation, such as optical absorption, scattering, uniformity, and mechanical quality.

Three key features have been identified as the goal of the material research investigation needed for our purposes. The first requirement is **low optical losses**, in order to maximize the ITF's power recycling gain, thus increasing circulating power and reducing shot noise.

Secondly, **low absorption** minimizes the impact of thermal lensing on the performance of the ITF. Finally, **low mechanical losses** in the coating and substrates minimize the motion of the reflective surface of the Fabry-Perot arm cavities due to TN.
From the point of view of mechanical losses, this line of research has successfully led to a deeper understanding of energy dissipation due to the anelastic behaviour of amorphous materials. This is explained by the presence of a number of metastable states; any pair of these states that are separated by an energy barrier is called Two-Level System (TLS): the higher the density of TLS is, the higher the loss angle. Thus, producing amorphous materials with a low density of TLS, or with an optimal distribution of TLS in terms of their barrier height, is the way to be pursued together with post-deposition treatments such as *annealing* [4].

Proposed research

In this project, I propose the investigation of a new family of amorphous materials, High Coordination Number Glasses (HCNG).
A key physical insight, embodied in Philip's conjecture [5], has led to the identification of these materials as a viable solution for our purposes. The conjecture states that amorphous films of materials whose atomic coordination numbers are equal to or greater than three should lead to a low number of TLS. In fact, for an atom that is weakly coordinated with its neighbors, it is easier for local structural rearrangements to occur; on the other hand, if an atom is linked to at least three others, the structure is more rigid and the TLS are unlikely, therefore reducing the mechanical dissipation. The structural units of these high-number coordination materials are often linked via their edges or their faces, making structural reorganization particularly difficult.

There are already a few candidate materials of interest, namely amorphous silicon (a_Si), cadmium telluride (a_CdTe), and indium phosphide (a_InP), which have the advantage of already being the subject of considerable attention in the scientific community, for their usefulness in the fields of microelectronics and photovoltaic cells [7]. Given this, a project (INFN_COAT) has been financed by the INFN to undertake a thorough study of these materials, and to which I intend to contribute with a research program combining both simulation of the physical properties and experimental characterization, articulated in the following steps:

1. Simulations of the expected mechanical properties of various candidate materials, both at room temperature and at cryogenic conditions, using a Finite Element Analysis software (e.g., Ansys).

2. Measurements of these thermo-mechanical properties by using the experimental set-up hosted in Urbino. Most importantly in this context, the experimental characterization performed with GeNS (Gentle Nodal Suspension) allows the measurement of mechanical loss and elastic constants of the samples used. These results can be compared with the simulations obtained from point 1 and with results obtained from the collaboration with other laboratories (e.g. GeNS experiment in Tor Vergata). In order to gain a greater physical understanding of the system, the measurement of the thermal noise dissipation performed by GeNS may also be

analyzed in light of the dynamic-molecular simulations performed by the Pisa group, to get some insight into the microscopic mechanisms related to the TLS distribution.

3. Widening the scope of these measurements, these properties may be explored as a function of the temperature conditions, by performing measurements at both room and cryogenic temperatures. In this way, I will be able to completely characterize the dynamical and thermo-dynamical behaviour of these systems. This is of paramount importance in order to achieve a complete picture of their physics, which in turn will serve as a guide for the identification of possible new candidate materials hitherto unexplored.

4. The proposed studies of the mechanical and thermal properties will be coupled with characterizations of the morphology by Scanning Electron Microscopy and Atomic Force Microscopy, performed at Tor Vergata, Perugia, Padova, and Salerno.

5. By taking advantage of the VCR&D collaboration, it will be possible to obtain the chemical composition (by Energy Dispersive Spectroscopy) to check the stoichiometry and/or the presence of dopants.

6. Study of the structure and the occurrence of crystalline phases can be performed by Raman, IR, and X-rays experiments hosted at Camerino, Perugia, Genova, Pisa, and Sapienza.

7. Phonons propagation can be investigated by Brillouin spectroscopy at Perugia.

Expected outcomes

This work project aims the identification of the best material candidates for next-generation interferometers by obtaining their complete characterization, and ultimately determining their suitableness to be used in the detectors. The comprehensive approach outlined in the steps above will allow a complete picture to emerge from the pursuit of many different physical lines of investigation.

Bibliography

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Description of the research in the three-year period

- First year :
    - study of the literature about coating R&D, the underlying theory of condensed matter physics, and the materials that can be good candidates.
    - Development of Ansys code to get mechanical simulations of candidates as a function of temperature.
- Second year :
    - GeNS measurements of the chosen candidates.
    - Morphological and structural measurements.
- Third year :
    - Final characterization of the optimal candidates (after a thermo-mechanical, morphological, and structural selection).
    - Suggestions for future development and research, and final thesis.