Coatings for Gravitational Wave Detectors

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Abstract: This article gives an overview of optical coatings for gravitational-wave detectors, presenting considerations about candidate coating materials to further improve the sensitivity of the Advanced LIGO and Virgo detectors and of detector generations beyond.

1. Introduction

In 2015, gravitational waves (GWs) were detected for the first time [7] by the Advanced LIGO gravitational-wave detectors [6]. Since then, many detections have been made [8, 9], the majority of which was also observed by the Virgo detector [2]. Most recently, shortly before the detectors went into an upgrade phase, Advanced LIGO and Virgo were joined by KAGRA [3], the first detector operating cryogenically.

These GW detectors are enhanced Michelson interferometers, several kilometers in length, which monitor the distance between suspended mirrors, see Fig. 1(a) for a schematic view. The mirrors at the ends of the detector arms, the so-called end test masses (ETMs), have high reflectivity of $\approx 99.9995\,\%$ and form cavities with the input test masses (ITMs) which have a lower reflectivity of about 99.5 %.

Brownian thermal noise of these ETM and ITM coatings is one of the main noise sources in current (and planned future) detectors, as such thermally driven elastic dissipation of the coating materials effectively cause a displacement noise of the mirror surfaces, equivalent to the distance changes the detectors aim to observe. Figure 1(b) shows the modelled sensitivity of Advanced LIGO (black curve) which is composed of different noise sources: the red line shows coating thermal noise, limiting the sensitivity in the most sensitive frequency band between a few ten and a few hundred Hz, together with quantum noise [13].

Coating Brownian noise in a GW detector is proportional to the square root of the coating thickness, the coating mechanical loss and the mirror temperature, and inversely proportional to the laser-beam diameter on the mirror [18], resulting in the aim for large mirrors and coating materials with low mechanical loss. Further requirements are low optical absorption of $< 10^{-6}$ of the incident laser light (to minimize thermal deformation or heating), low scattering, high thickness homogeneity and the least amount of point-like defects possible.

The following sections will give a brief overview of coating materials currently used, and those considered for future detectors, summarizing the challenging aim of realizing large-scale mirrors with low Brownian thermal noise and low optical absorption of the coatings, while minimizing defects and scattering.

2. Coatings for Advanced LIGO and Virgo, and their upgrades

The coatings currently used in Advanced LIGO and Virgo are dielectric coatings comprised of amorphous silica (SiO_2) and tantala (Ta_2O_5), deposited on silica substrates. The tantala is doped with titania (TiO_2) which can reduce the mechanical loss by up to 25 % (in this article, tantala always refers to tantala doped with titania). Still, tantala has significantly higher mechanical loss than silica and therefore dominates the thermal noise of the coating stacks [16]. The coatings are currently produced by LMA[1] via ion beam sputtering. Figure 1 shows a photo of of two of the LIGO ETMs, each 34 cm in diameter, inside the coating chamber after the coating was deposited. These coatings show a very low optical absorption of ≈ 0.25 ppm at the operating wavelength of 1064 nm, corresponding to an extinction coefficient k in the 10^{-7} range [14].

To lock the interferometer, laser light at 532 nm, half of the operating wavelength, is used. To achieve reflectivity at both wavelengths, the coating design diverts from quarter layers, to slighty thicker silica and thinner tantala

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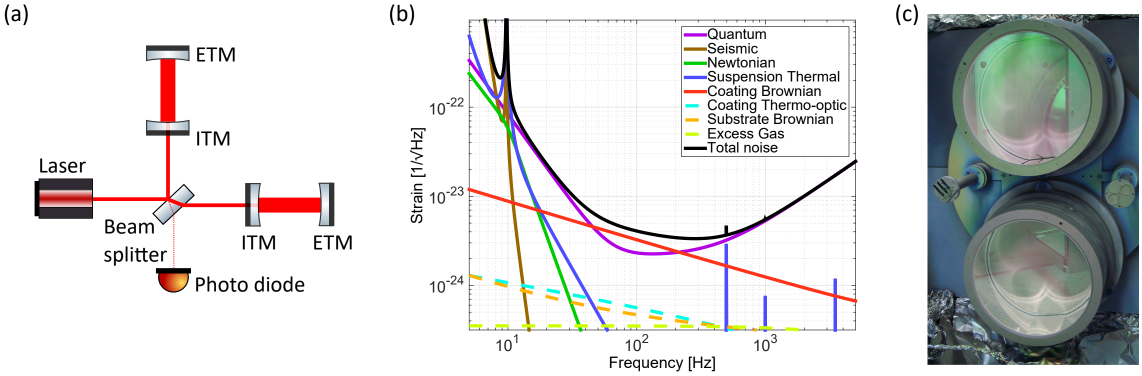

Fig. 1. (a) Simplified schematic of a GW detector with arm cavities made of highly-reflective end test-mass mirrors (ETMs) and input test-mass mirrors (ITMs) lower in reflectivity. (b) Typical modelled sensitivity curve for Advanced LIGO (graph from LIGO [13]). (c) Photo of two of the LIGO ETM mirrors, 34 cm in diameter, inside the coating chamber (image credit: LMA).

layers. Although thermal noise levels are lowered using this non-quarter wavelength design [10], it still must be reduced by about a factor two to reach the design sensitivity of the next upgrades to current detectors, Advanced LIGO+ and Advanced Virgo+. For these upgrades, new amorphous coating materials have been developed and are currently under investigation for replacing tantala:

- Titania doped germania (Ti:GeO_2) demonstrates a mechanical loss meeting the requirements of the Advanced LIGO+ upgrades [23]. This is currently the material of choice for the upgrades, however some challenges remain as heat treatment at the temperatures required to achieve this loss level and also low absorption causes significant bubble-like defects in multilayer coatings. Research is ongoing to identify a deposition and/or post-deposition recipe that can reliably reproduce bubble-free coatings.
- Silicon nitride (SiN_x) shows low mechanical loss, but its optical absorption is too high ($10^{-5} < k < 10^{-6}$ at 1064 nm [17]). Research to further reduce the absorption to make SiN_x suitable for GW detectors is ongoing.
- Titania doped silica (Ti:SiO_2) is an interesting composition of materials known to have low absorption and mechanical loss, which may serve as a high-index material. However, work on this material is an earlier stage than that on doped germania or SiN_x.

3. Coatings for future gravitational-wave detectors

Further upgrades are planned beyond Advanced LIGO + and Advanced Virgo +, including upgrades within the current facilities and entirely new GW detectors in which a significant reduction in coating thermal noise is required. To realize this, the development of new materials with lower mechanical loss will remain an important challenge to overcome. In addition, the European *Einstein Telescope* [1]) and the US *Voyager* [15] plan operation at cryogenic temperatures. The US *Cosmic Explorer* plans with increased mirror sizes, and a potential upgrade to cryogenics at a later stage [21].

- The possibility to use longer laser wavelengths in the next generation of detectors - under consideration are 1550 nm or ≈2 µm - opens up new options for coating materials:
  - Amorphous silicon (a-Si) shows low mechanical loss, however, the lowest optical absorption realized corresponds to $k = 1.22 \times 10^{-5}$ at 1550 nm [4]. Work on reducing the absorption is ongoing.
  - SiN_x is not only interesting at room temperature (see Sec. 2), but also shows a low cryogenic mechanical loss [20], making further research into realizing low absorption at longer wavelengths interesting.
- Other techniques explored within the GW community to improve amorphous coatings are:
  - Nano layers - quarter layers sub-structured into thinner layers - can suppress crystallization and raise the tolerable heat treatment temperature [19]. This can further improve properties such as the mechanical loss or optical absorption, and/or help to match the tolerable maximum heat-treatment temperature of one material in the coating stack to the needs of the second material.
  - Multimaterial coatings, in which more than two materials are used, are composed of a few double-layers of low-absorption layers to reflect the majority of the incident laser light, while further down in the stack, materials with higher optical absorption, but low mechanical loss can be used [22].
- An interesting alternative are crystalline coatings, which are grown by molecular-beam epitaxy on crystalline substrates with matching lattice structure.

– GaAs/AlGaAs, grown on GaAs wafers, shows low thermal noise and low absorption optical absorption [5]. However, for use in GW detectors, those coatings have to be upscaled to ≈30 cm which would involve significant costs [12]. Research into alternative crystalline coating materials is planned.
– Cryogenic detectors plan to use mirror substrates made of crystalline silicon or sapphire. This offers the attractive option of growing crystalline coatings, made of lattice-matched materials, directly on the crystalline substrates, such as e.g. AlGaAP/GaP on silicon [11] – making a substrate transfer and bonding procedure unnecessary, as required e.g. to use AlGaAs/GaAs on fused silica.

4. Conclusion

This article gives an overview of coating materials currently used in or under consideration for GW detectors[2]. While mirrors with world-class performance regarding low absorption and thermal noise~~,~~ and with large-scale homogeneity have been realized, further improvements meeting the strict requirements on many material properties simultaneously remains challenging. Therefore, coating research continues to be an active area of research within the GW community, in particular in the light of planned future detectors.

References

1. M. Abernathy et al. Einstein gravitational wave telescope (ET) conceptual design study, 2011.
2. F. Acernese et al. Advanced Virgo: a second-generation interferometric gravitational wave detector. Class. Quant. Grav., 32(2):024001, 2015.
3. T. Akutsu et al. Overview of KAGRA: Detector design and construction history. Progress of Theoretical and Experimental Physics, 2021(5), 2020. 05A101.
4. R. Birney et al. Amorphous silicon with extremely low absorption: Beating thermal noise in gravitational astronomy. Phys. Rev. Lett., 121:191101, 2018.
5. G. D. Cole et al. High-performance near- and mid-infrared crystalline coatings. Optica, 3(6):647–656, 2016.
6. LIGO Scientific Collaboration and Virgo Collaboration. GW150914: The Advanced LIGO detectors in the era of first discoveries. Phys. Rev. Lett., 116:131103, 2016.
7. LIGO Scientific Collaboration and Virgo Collaboration. Observation of gravitational waves from a binary black hole merger. Phys. Rev. Lett., 116:061102, 2016.
8. LIGO Scientific Collaboration and Virgo Collaboration. GWTC-2: Compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run. Phys. Rev. X, 11:021053, 2021.
9. The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration. GWTC-3: Compact binary coalescences observed by LIGO and Virgo during the second part of the third observing run, 2021.
10. A. E. Villar et al. Measurement of thermal noise in multilayer coatings with optimized layer thickness. Phys. Rev. D, 81:122001, Jun 2010.
11. A. V. Cumming et al. Measurement of the mechanical loss of prototype GaP/AlGaP crystalline coatings for future gravitational wave detectors. Classical and Quantum Gravity, 32(3):035002, 2015.
12. G. M. Harry et al. In Optical Interference Coatings Conference (OIC) 2022.
13. L. Barsotti et al. The updated Advanced LIGO design curve, 2018.
14. L. Pinard et al. Mirrors used in the ligo interferometers for first detection of gravitational waves. Appl. Opt., 56(4):C11–C15, Feb 2017.
15. R. X. Adhikari et al. A cryogenic silicon interferometer for gravitational-wave detection. Class. Quant. Grav., 37(16):165003, 2020.
16. M. Granata et al. Amorphous optical coatings of present gravitational-wave interferometers. Classical and Quantum Gravity, 37(9):095004, apr 2020.
17. M. Granata et al. Progress in the measurement and reduction of thermal noise in optical coatings for gravitational-wave detectors. Appl. Opt., 59(5):A229–A235, 2020.
18. G. Harry et al. Thermal noise from optical coatings in grav. wave detectors. Appl. Opt., 45(7):1569–1574, 2006.
19. H.-W. Pan et al. Thickness-dependent crystallization on thermal anneal for titania/silica nm-layer composites deposited by ion beam sputter method. Opt. Express, 22(24):29847–29854, 2014.
20. H.-W. Pan et al. Silicon nitride and silica quarter-wave stacks for low-thermal-noise mirror coatings. Phys. Rev. D, 98:102001, 2018.
21. D. et al. Reitze. Cosmic explorer: The u.s. contribution to gravitational-wave astronomy beyond LIGO. Bulletin of the AAS, 51(7), 2019. https://baas.aas.org/pub/2020n7i035.
22. S. C. Tait et al. Demonstration of the multimaterial coating concept to reduce thermal noise in gravitational-wave detectors. Phys. Rev. Lett., 125:011102, 2020.
23. G. Vajente et al. Low mechanical loss TiO_2:GeO_2 coatings for reduced thermal noise in gravitational wave interferometers. Phys. Rev. Lett., 127:071101, 2021.

[2]This article only gives a brief summary of a selection of materials and techniques for coating improvement. A much larger variety of materials, deposition techniques and optimisation processes are under investigation. Many other material properties such as optical scattering, Young's modulus and thermo-optic and thermo-elastic parameters are of high relevance and under investigation by several research groups.