3版

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　４年　６月２９日現在

機関番号： ６２６１６
研究種目： 基盤研究(C)（一般）
研究期間： 2019～2021
課題番号： １９Ｋ０３８９７
研究課題名（和文） Crystalline mirrors with minimal thermo-optic noise for space-time metrology

研究課題名（英文） Crystalline mirrors with minimal thermo-optic noise for space-time metrology

研究代表者
Ｆｌａｍｉｎｉｏ　Ｒａｆｆａｅｌｅ（Flaminio, Raffaele）

国立天文台・重力波プロジェクト・特別客員研究員

研究者番号：１０７２３１０８

交付決定額（研究期間全体）：（直接経費）　　2,600,000円

研究成果の概要（和文）：重力波の検出に使用されるミラーの熱雑音は、検出器の感度を制限する主な要因の一つである。本研究では、GaAs/AlGaAs多層膜を用いたミラー（AlGaAsミラー）について検討した。ミラーの熱雑音を直接測定するために、テーブルトップ型短尺光共振器と同様の小さなレーザービームを照射したミラーにおける熱光学雑音の影響を初めて評価した。並行して、熱雑音を最小化するように最適化された直径2.5cmのAlGaAsミラーの光学性能を評価した。ミラーの散乱光、粗さ、点欠陥の測定を行った。最後に、直径10cmのAlGaAsミラーを実現し、その光学的性能を測定した。

研究成果の学術的意義や社会的意義
本研究は、その結果に基づき重力波検出器の感度の向上を図ることができるため、重力波天文学に有用である。さらに、オプトメカニカル研究、レーザー周波数安定化、光時計、垂直外部共振器面発光レーザー、ジャイロレーザーなど、他の科学技術分野への応用も期待される。

研究成果の概要（英文）：The thermal noise of the mirrors used for the detection of gravitational waves is one of the main limitation to the detector's sensitivity. In this research we investigated mirrors based on GaAs/AlGaAs multi-layers coatings (called AlGaAs mirrors). We evaluated, for the first time, the effect of the thermo-optic noise in mirrors used with small laser beams as the ones used in table-top short optical cavities for the direct measurement of mirror thermal noise. In parallel, we characterized the optical performances of a 2.5 cm diameter AlGaAs mirrors optimized so to minimize its thermo-optic noise. We measured its scattering, its roughness and its point defects. Finally we realized AlGaAs mirrors with 10 cm diameter and we measured their optical performances.

研究分野： gravitational wave astronomy

キーワード： gravitational wave　mirror　crystal　coating　thermal noise

１．研究開始当初の背景

Gravitational waves are ripples of space-time predicted by Einstein in his theory of general relativity. Their detection allows to “see” phenomena invisible to other types of astronomical observatories. Indeed, gravitational waves from the merger of black holes observed first by Advanced LIGO in the USA and, afterwards, by Advanced Virgo in Europe have revealed a new family of black holes never seen before. The first observation of a gravitational wave from the merger of two neutron stars in coincidence with the detection of a gamma ray burst, and the subsequent observation of the explosion by many ground-based and space observatories, have produced a plethora of results. These observations marked the beginning of gravitational wave astronomy. More mergers of black holes and neutron stars will be observed as the detectors sensitivity will be improved. New types of gravitational wave sources will become visible. For all these reasons, the increase of the sensitivity of gravitational wave observatories is a priority for fundamental physics and astronomy.

Gravitational wave detectors are based on Michelson-type laser interferometers with arms several km in length. The mirrors of the interferometers are large cylinders made of fused silica or sapphire, coated with high reflectivity coatings, and suspended to complex vibration isolation systems. An ultra-stable laser beam measures the change in the interferometer differential arm length. The length variations to be measured are tiny, of the order of 10^{-19} m. At this level of sensitivity, the mirror thermal noise limits the performances in the region of frequencies where the detector sensitivity is the best i.e. around 100 Hz. In order to improve the sensitivity of these detectors it is thus essential to reduce the mirror thermal noise. According to the fluctuation-dissipation theorem, the position of any mechanical system is affected by fluctuations whose amplitude depends on the system’s internal friction. This implies that the mirror thermal noise can be reduced if the mirror internal friction in the detector bandwidth is reduced. Measurements have shown that most of the friction in the mirrors resides in the high reflective coatings. For this reason, scientists are looking for high quality optical coatings with the lowest possible mechanical losses. High quality optical coatings used in mirrors for gravitational wave detectors are made of amorphous materials deposited by ion beam sputtering. The best material found so far are silica for the low index of refraction material and a titania/tantala mixture for the high index material. In general, crystals have lower mechanical losses than amorphous materials. This consideration has pushed the development of coatings based on crystalline coatings. So far, the best results have been obtained with multilayers made of AlAs and GaA (usually referred to as AlGaAs coatings). The AlGaAs coatings have internal mechanical losses about ten times smaller than the coatings currently used in gravitational wave detectors. Moreover, while mechanical losses in amorphous coatings increase at cryogenic temperature, the AlGaAs coatings improve, making these coatings a good candidate also for gravitational wave detectors operated at cryogenic temperature like KAGRA.

２．研究の目的

The purpose of this project is to develop new crystalline mirrors with lower thermal noise. This development will affect several fields of basic research. Indeed coating thermal noise does not affect only the performances of gravitational wave detectors. Other fields of research making use of high finesse optical cavities face similar issues. Among these, there are optical atomic clock, quantum opto-mechanics and cavity quantum electro-dynamics.

The development of crystalline coatings has shown that these coatings have lower internal friction and so lower coating Brownian noise. On the other hand, thermo-elastic noise and thermo-refractive noise have a stronger impact in crystalline coatings than in standard amorphous coatings. These two noises turn out to be coherent since they are both driven by thermo-dynamical fluctuations in the coatings. For this reason, they are collectively referred to as thermo-optic noise. In some materials, the two effects (density and index of refraction variation with temperature) tend to compensate since the index of refraction decreases when the material expands. Therefore, by properly designing the coating structure it is possible to achieve a good compensation thus reducing the total thermo-optic noise. Such a design requires a detailed modeling of the thermo-elastic and thermo-refractive noise in the coating layers. In this project, we wish to do such a detailed modeling and to use it to develop crystalline mirrors with minimized thermo-optic noise. At the same time we wish to check that the thermo-optic minimized design is compatible with the required optical specifications of high reflectivity, low optical absorption and low light scattering. To our knowledge such a detailed modeling and design has not been done so far. Finally yet importantly, we wish to develop AlGaAs mirrors with larger diameter compared to the ones built so far.

３．研究の方法

The research methods followed three main lines.

First, we developed a model to calculate the effect of thermo-optic noise in multilayer coatings as a function of the coating design, coating material parameters, beam size and beam shape. In particular, we were interested in calculating how this noise changes when the beam size becomes small compared to the thermal propagation length of the heat in the coating material. This is more relevant for crystalline coatings since these materials conduct heat more efficiently than amorphous materials. We were also interested in studying the case where the coatings are illuminated with a Hermite-Gauss beam i.e. not a simple Gaussian beam. Both these studies were motivated by the fact that small and high order modes laser beams are used to measure the effect of thermal noise with tabletop short high finesse cavities.

In parallel, we develop a one inch mirror whose coating design had been optimized to minimize the effect of thermo-optic noise. This work was done in collaboration with the company CMS. The optical performances of the mirror were characterized in terms scattering, roughness and point defects.

Finally yet importantly, we develop the technology to build crystalline AlGaAs mirrors 10 cm in diameter. To this purpose, we first realize 10 cm AlGaAs coatings on 10 cm diameter GaAs wafers. Then we characterized these coatings to measure their scattering as well as their roughness and their point defects. Finally, we developed the technique to transfer these relatively large coatings on 10 cm diameter silica substrates.

４．研究成果

Coating thermo-optic noise is the coherent combination of thermo-elastic noise and thermo-refractive noise, both driven by temperature fluctuations in the mirror. The evaluation of these noises in the case of laser beams much larger than the heat propagation length in the mirror is well known. Table-top prototypes aiming at measuring the coating thermal noise do not satisfy this condition and for this reason we developed a general model. In order to do so, we first consider the coating as a single thick layer of material having properties equal to the average of the two materials composing the multilayer stack. We then solve the heat propagation differential equation when entropy is injected into the coating. To calculate the case of the thermo-elastic noise entropy was injected in the entire coating while in the case of thermo-refractive noise entropy was injected only at the coating’s surface. The two cases were then combined coherently and from the temperature distribution in the coating we deduced the thermo-optic noise i.e. the equivalent mirror displacement noise as measured by a laser beam. The result is shown in the Figure below.

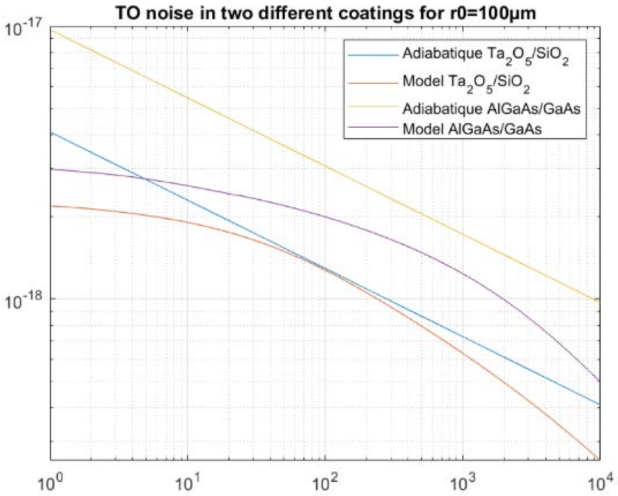

Figure 1. Thermo-optic noise in m/√Hz as a function of frequency (Hz) for Ti:Ta2O5/SiO2 coating and GaAs/AlGaAs coatings and a laser beam 100 μm in radius. The straight lines show the same noise evaluated in the adiabatic approximation i.e. when the laser beam is much larger than the heat propagation length in the mirror materials.

At low frequency, the heat propagation length becomes larger than the beam size and the noise is smaller than the one foreseen by the adiabatic approximation. Similarly, at high frequency the noise is entirely due to the temperature fluctuations in the coating, which are smaller than in the substrate. Both effects are stronger in crystalline coatings thus making the difference with respect to the adiabatic model larger in this case.

We then developed a more detailed model of the thermo-optic noise considering the multilayer structure of the coating. The results in the case of a multilayer coating is shown the figure below.

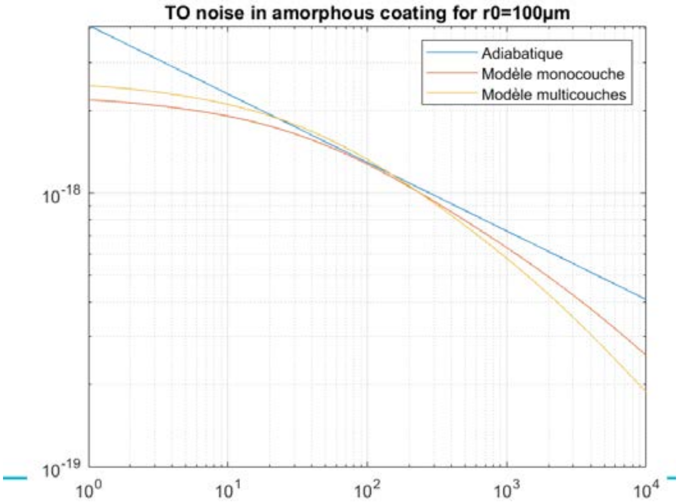

Figure 2. Thermo-optic noise in $m/\sqrt{Hz}$ as a function of frequency (Hz) for a Ti:Ta_2O_5/SiO_2 coating and a laser beam 100 μm in radius. The monolayer model and the multilayer model are compared.

The result show that the two models gives very similar results and the same features at low frequency and at high frequency.

Following the results from the simulation as well as other works available in literature, we realized a mirror whose multilayer had been optimized to minimize thermo-optic noise. This was done in collaboration with the CMS Company. The optimization was done by varying the layers thickness so that the thermo-elastic noise originating from the bulk of the coating and the thermo-refractive noise originating from the layers closer to the coating surface compensate each other as much as possible. A picture of the mirror is shown in the figure here below.

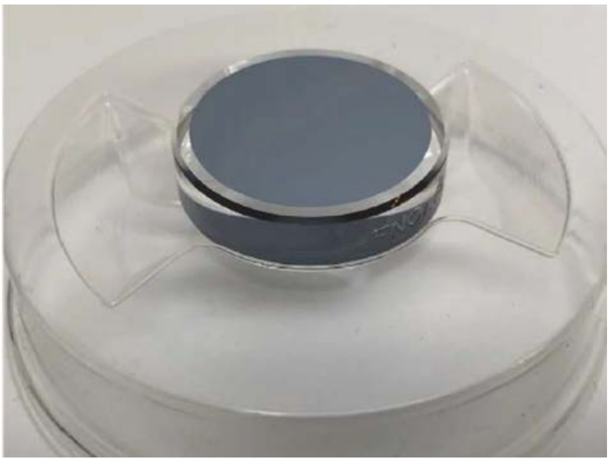

Figure 3. 1-inch diameter mirror made of an optimized GaAs/AlGaAs coating in order to minimize the effect of thermo-optic noise.

The mirror was characterized in terms of scattering, point defects and roughness. The measured average scattering was about 9 ppm. This is a very good value, comparable to the one measured on the large mirrors used for gravitational wave detection. The density of point defect was 0.5 defects per mm^2. This is only a factor of two larger than the one measured on the mirror used for gravitational wave detection. Finally, the roughness was measured and found to be about 1 angstrom, similar to the value measured on the mirrors used for gravitational wave detection. Overall, the quality of the mirrors appeared very close to the specifications required for the mirrors of gravitational wave detectors. It should be noted that this was a 1-inch mirror, so very small compared to the 35 cm diameter mirrors used in gravitational wave detectors. Realizing these mirrors on such large diameter is the challenge to address in order to use this technology in gravitational wave detectors.

The last part of this research was indeed to develop GaAs/AlGaAs mirror 10 cm in diameter.

We first realized and characterized multilayer GaAs/AlGaAs coatings grown by Molecular Beam Epitaxy on 10 cm diameter GaAs wafers. Two type of coatings were realized. The first was made by a thick etch stop AlGaAs layer, a GaAs/AlGaAs doublet and finally a thick GaAs layer. The second coating was similar but instead of a single doublet there 35 doublets between the two thick layers. These coatings were characterized in terms of scattering and point defects. Moreover, the transmission was measured as a function of the wavelength to check that they comply with the optical design. The figure below show the transmission of the “doublet” type of coating as a function of the wavelength. The measured spectrum agrees well with the model.

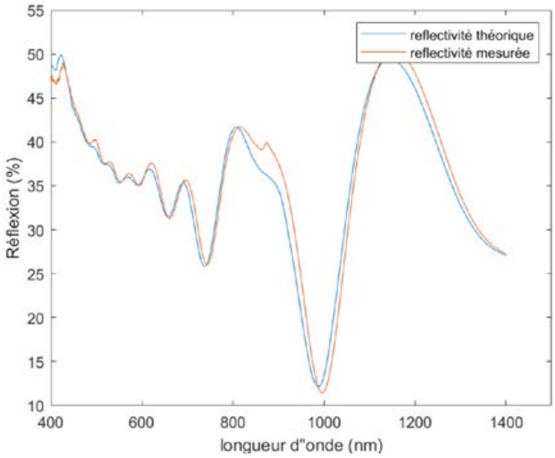

Figure 4. The spectrum of the reflection of the “doublet” type GaAs/AlGaAs coating as a function the wavelength. The measurement is compared to the model.

The scattering measured on the multilayers was in the range 75 ppm to 90 ppm depending on the sample. The density of point defects was about 1 to 2 per mm^2. Even if these values were not as good as the one measured on the small mirror we decided to proceed with the transfer of the coatings from the original GaAs wafer to the final silica substrates. The latter were 10 cm diameter and 500 μm thick silica wafers.

The first step of the transfer was the cleaning and the preparation of the coating surface. Then a 500 nm think silica layer was deposited by Plasma-Enhanced Chemical Vapor Deposition on the top of the coating. After deposition, the surface was polished via a chemical-mechanical polishing. A similar polishing process was applied on the silica surface in order to have a smaller roughness. Once the two surfaces had been properly prepared, they were brought into contact and adhered. Finally, the last part of the process consist in removing the original GaAs wafer so to leave only the coating on the silica substrate. This was done using grinding and then chemical etching.

This process was applied first to the “doublet” type coating and then to the multilayer. The pictures below show the GaAs/AlGaAs doublet coating and the multilayer after transfer on the silica wafer.

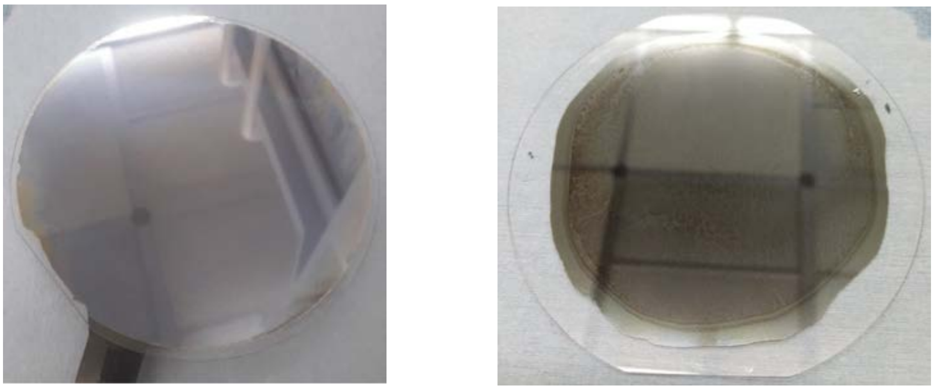

Figure 5. The doublet (left) and the multilayer (right) after the transfer on the silica wafer.

The transmission spectrum of both coatings were measured and were found to agree well with the design of the original coating.

In the case of the doublet, we also perform several optical characterizations. We measured again the scattering, the point defects and the roughness. All these parameters were found to be comparable to ones measured before the transfer showing that the transfer had kept the quality of the original coating. In the case of the point defects a small decrease in their density was found. This can be explained as defects develop during the Molecular Beam Epitaxial growth so that their density is lower in the first layers i.e. the ones that are at the top of the coating after the transfer.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　1件／うちオープンアクセス　1件）

１．著者名 Manuel Marchio, Matteo Leonardi, Marco Bazzan & Raffaele Flaminio	４．巻 11
２．論文標題 3D characterization of low optical absorption structures in large crystalline sapphire substrates for gravitational wave detectors	５．発行年 2021年
３．雑誌名 Scientific Reports volume 11, Article number: 2654 (2021)	６．最初と最後の頁 2654 1-8
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41598-020-80313-1	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計6件（うち招待講演　6件／うち国際学会　0件）

１．発表者名 Raffaele Flaminio
２．発表標題 Crystalline coatings to reduce mirror thermal noises
３．学会等名 KAGRA Face-To-Face Meeting（招待講演）
４．発表年 2020年

１．発表者名 Victor Hui
２．発表標題 A model of the coating thermo-elastic and thermo-refractive noises in gravitational wave detectors
３．学会等名 Journees de Rencontre des Jeunes Chercheurs（招待講演）
４．発表年 2019年

１．発表者名 Matteo Leonardi
２．発表標題 MIR subsystem report
３．学会等名 KAGRA F2F Meeting（招待講演）
４．発表年 2019年

１．発表者名
Victor Hui, Raffaele Flaminio et al.

２．発表標題
Transfer of AlGaAs multilayer on silica substrate

３．学会等名
LIGO-Virgo-KAGRA collaboration meeting（招待講演）

４．発表年
2022年

１．発表者名
Victor Hui, Christophe Dubarry and Raffaele Flaminio

２．発表標題
Development of a crystalline mirror by transfer of a AlGaAs/GaAs multilayer coating on a silica substrate

３．学会等名
Cinquieme Assemble Generale du GdR Ondes Gravitationnelles（招待講演）

４．発表年
2021年

１．発表者名
Matteo Leonardi

２．発表標題
Status of KAGRA mirrors

３．学会等名
Gravitational wave advanced detectors workshop（招待講演）

４．発表年
2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究分担者	ＬＥＯＮＡＲＤＩ　ＭＡＴＴＥＯ (Leonardi Matteo) (90816448)	国立天文台・重力波プロジェクト・助教 (62616)	

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
フランス	CNRS/LAPP	CNRS/LMA	CEA/LETI	
イタリア	Universita di Padova			