An Optical absorption measurement system used to characterize KAGRA sapphire mirrors

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Abstract

KAGRA is the Japanese gravitational wave interferometer detector. It uses sapphire as the main mirror and works at cryogenic temperature (20K) in order to reduce mirror thermal noise. We built an optical absorption measurement system based on the "Photothermal Common-path Interferometer" technique to measure the absorption coefficient of both bulk and surface in order to characterize high-quality optical mirrors, we are able to measure the absorption coefficient continuously along all three axes of different samples to create 3D absorption maps with a sensitivity of 2ppm/cm. In this work, I present this system and its application with concrete examples of our measurements.

1. Introduction

KAGRA [1] is a Japanese 3 km laser interferometer in which NAOJ takes a leading role for construction, maintenance, and future upgrade. It will be operated with detectors in the US (advanced LIGO [2]) and Europe (advanced Virgo [3]). KAGRA and the other detectors are called second-generation gravitational-wave detectors. The current sensitivity of these detectors is limited at mid-frequencies (10-100 Hz) by mirror thermal noise. In order to overcome this limitation, KAGRA, for the first time, works at cryogenic temperature to reduce mirror thermal noise. Therefore, it needs to use sapphire as the main mirror substrates. The mirror thermal noise can be divided into two parts; one is coming from the sapphire bulk absorption which depends on the material quality itself, the other is due to the high-reflectivity coating absorption. The requirement for the bulk absorption coefficient of sapphire is 50 ppm/cm, for the coating absorption, it is less than 1ppm [4].

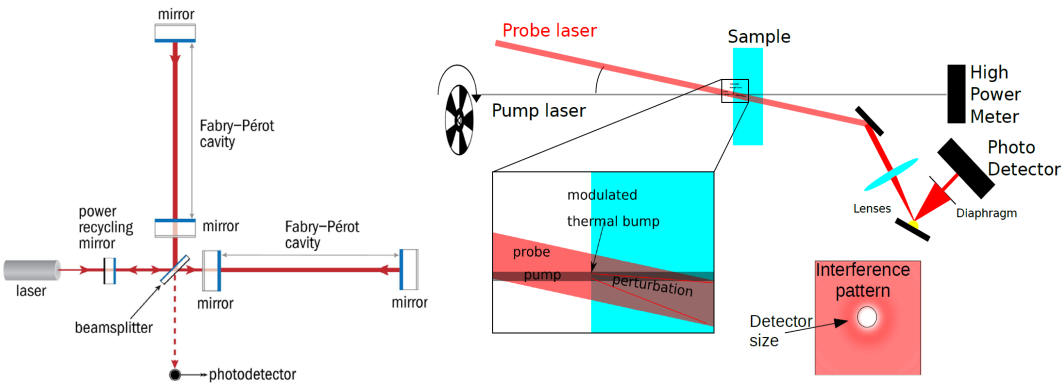

Figure 1: Left: KAGRA is a Michelson interferometer with two Fabry-Perrot cavities and an arm length of 3 km for each arm. Right: The working principle of the Photo-thermal Common-path interferometer technique.

Sapphire is a crystalline form of aluminum oxide, Al_2O_3. The crystal has a trigonal hexagonal scalenohedral structure. It has one C-axis as the symmetry center and three A-axes indicating the hexagonal structure of the crystal. The angle between the three A-axes is 60 degrees [5]. The fabrication of large sapphire substrates with our constraints is a technological challenge for companies, and the causes of sapphire absorption are not completely understood. Due to the change in parameters (temperature, pressure, impurities, etc.) in the growth process, each crystal has a different absorption. Therefore, each sample needs to be measured individually. For these reasons, it is very important to develop an absorption measurement system in NAOJ.

2. Absorption measurement system

We built an optical absorption measurement system based on the so-called Photo-thermal Common-path Interferometer (PCI) technique, as shown in Fig.1. Basically, we have two lasers in the system. A pump laser at 1064nm periodically modulated by a chopper with an incident power of 10 W, heats up the sample and creates a thermal lens. Then a probe laser interacts with the thermal lens which creates a perturbation interfering with the probe itself, the interference is proportional to the absorption rate. The pump beam's waist is 3 times smaller than the probe beam's waist to ensure the interference happens. The measurement requires the sample to be transparent to the probe lasers. For the sapphire substrate, we are using 633 nm as the probe, but we also have a 1310nm probe laser for other materials.

In order to detect the maximum interference signal, we reproduced it by using a converging lens in the out-going probe beam path and a small sphere mirror to subsequently detect the signal with a photodetector. We call this setup the imaging unit. It is placed 100 mm away from the sample in order to avoid intersection with the pump beam which is at an angle of 6 degrees with the probe beam. In the end, we got three signals: the DC, the demodulated AC from the photodetector and the chopper, and the power of the pump beam. Then the absorption rate is calculated by using the formula below:

$$Abs[cm^{-1}] = \frac{AC[V]}{DC[V] \cdot P[W] \cdot R[cm/W]} \qquad (2.1)$$

Where R is the calibration factor that depends on experimental and material parameters [4].

3. Experimental configuration and Features

1) Experimental configuration: As can be seen from Fig.2, The setup consists of three parts. The first part is the optical bench where we set the pump beam and the probe beam. The second part is the translation stage which holds the sample, the movable ranges for the X, Y, Z axes are both 250 mm. The last part is the imaging unit where the signal is received.

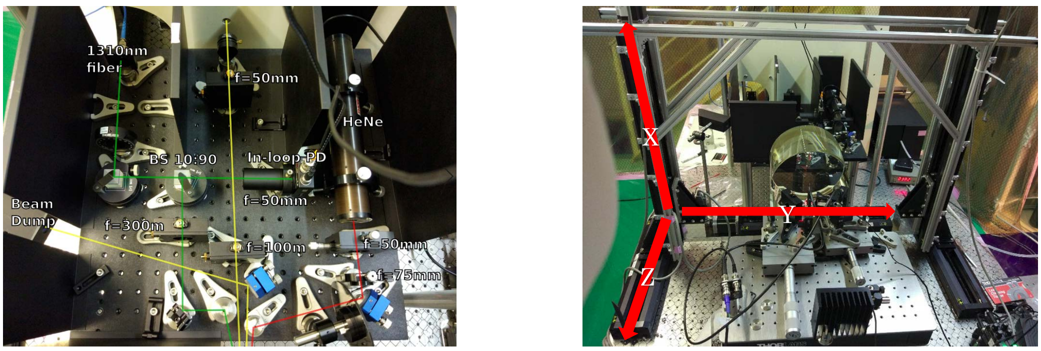

Figure 2: Left: the pump and the probe configuration. Right: the translation stage and the imaging unit. The red bars show the 3 axes of the stage.

As can be seen from Fig.3, We have three sample holders which can fulfill the absorption measurement requirements for different size of samples.

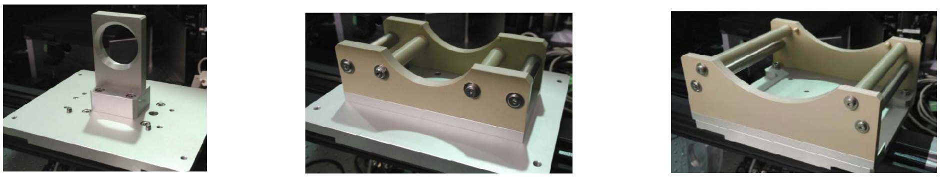

Figure 3: From left to right: a small mount for samples up to 2 inches in diameter, a mount for Tama300 mirror size samples (100 mm-diameter × 60 mm), and a mount for KAGRA test masses size sample (220 mm-diameter × 150 mm).

2) Feature: We can measure the absorption coefficient continuously along all three axes of different samples to create 3D absorption maps with a sensitivity of 2 ppm/cm. For the bulk and coating absorption, any material that is transparent to the probes can be measured at 1064nm. Also, we can measure samples of several sizes, from 1-inch in diameter to 22cm in diameter and 15cm in thickness, which corresponds to KAGRA-size mirror. For the translation stage, its spatial resolution is 0.1mm for the X, Y axes, and 1mm for the Z-axis.

4. Result of the measurement

1) coating absorption: As can be seen from Fig.4 and Fig.5, we have two coating measurement results. One is from a company Sigma-Koki, another is from ATC, NAOJ. Both of the coatings are placed on a fused silica substrate with 100mm in diameter and 30mm in thickness. The results are XY plane maps and show a similar absorption pattern. The one from Sigma-Koki shows a lower absorption rate and less coating defects (the dots on the maps) and has been chosen for the KAGRA installation.

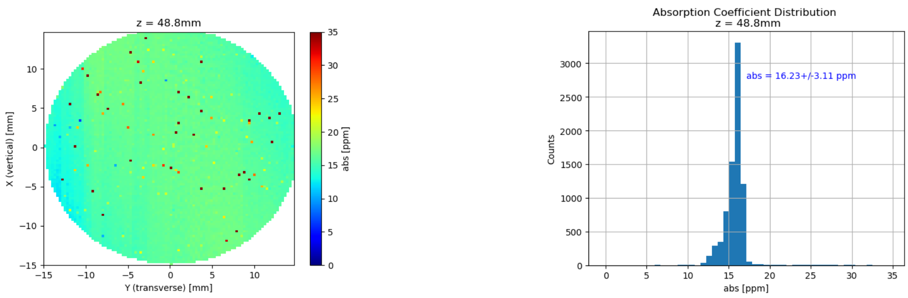

Figure 4: Sigma-Koki coating with mean absorption: abs = 16.23 ± 3.11 ppm. Left: XY plane absorption map. Right: Absorption coefficient distribution.

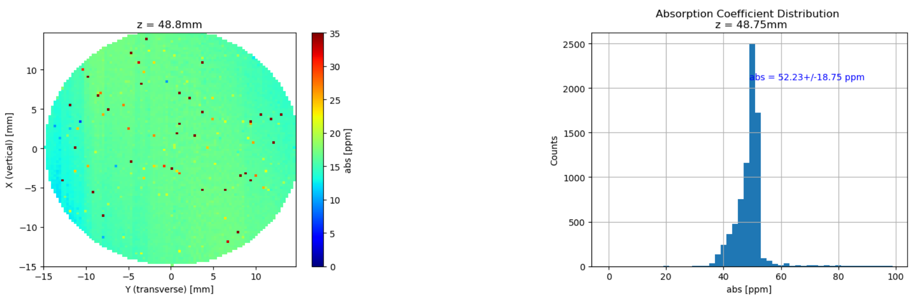

Figure 5: ATC coating with mean absorption abs = 52.23 ± 18.75 ppm. Left: XY plane absorption map. Right: Absorption coefficient distribution.

2) KAGRA-size samples bulk absorption: We tested the bulk absorption of one KAGRA-size sample. As can be seen from Fig.6, This sample didn't fulfill the KAGRA absorption requirements (<50 ppm/cm) so it is currently a spare sapphire substrate for KAGRA. The sample shows a very interesting star-like structure in the absorption map, which is correlated to the three A-axes of the sapphire structure, why this clear correlation appears is currently under investigation.

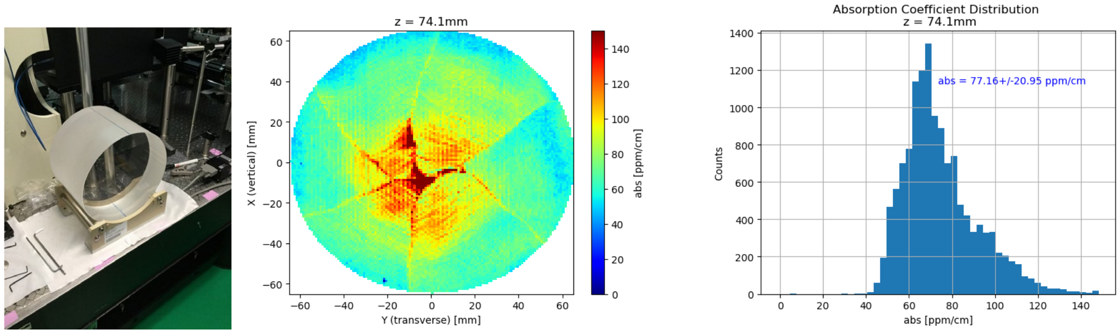

Figure 6: KAGRA-size sample with mean absorption: abs = 77.16±20.95 ppm/cm. Left: Sapphire substrate in the lab. Middle: XY plane absorption map. Right: Absorption coefficient distribution.

5. Summary

In this work, we presented the working principle of the PCI measurement system and the results of both bulk absorption and coating absorption. We are able to measure the absorption coefficient continuously along all three axes of different samples to create 3D absorption maps with a sensitivity of 2ppm/cm. Also, we found an interesting structure in large sapphire substrates and confirmed that sample by sample measurement is mandatory in the case of KAGRA. For the future plan, we will upgrade the measurement system. Including full automation of the system and remote control. We also work on input power and polarization optimization for the pump beam. For future KAGRA upgrades, lager sample holder for heavier and lager sapphire substrate are planned. Furthermore, we want to focus more on investigating the absorption property of different coatings. (e.g. crystalline coatings, which can further decrease the thermal noise of the KAGRA interferometer).

6. References

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