Measuring Birefringence Homogeneity in High-Quality Optical Substrates

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Abstract

For high-sensitive optical facilities using laser under cryogenic environments, ultra-high quality mirrors are essential. If, as in case for laser-interferometer like gravitational-wave detectors, some mirrors have to be semi-transparent, the use of crystalline substrates becomes mandatory, which easily leads to unwanted birefringence effects in case the substrate-crystal has inhomogeneities.
In order to easily characterize the homogeneity of birefringence in high-quality optical mirrors, we developed a measurement setup based on the "Photothermal Common-Path" (PCI) device, placed in the TAMA300 facility of NAOJ's Mitaka Campus. Here, I will describe our measuring approach and how we modified the PCI to do birefringence measurements with a spatial resolution of less than 0.5x0.5mm.

1. Introduction

In the Gravitiational-Wave Science Project at NAOJ, we are concerned mainly with the Japanese large-scale gravitational-wave detector KAGRA [1], which will soon join the international network of laser-interferometer based detectors around the world, currently consisting of the two LIGO detectors in the USA and the Virgo detector in Italy [2][3]. Our main focus is not only the construction and the maintenance of the KAGRA detector (in collaboration mainly with the Institute of Cosmic Ray Research - ICRR - of the University of Tokyo) but also research regarding future upgrades and developments with respect to KAGRA and gravitational-wave detection in general.
KAGRA will be the first large-scale laser-interferometer using cryogenically cooled main-mirrors in its cavities to detect gravitational-waves, which can be understood as being small ripples in space-time caused by the movement of masses. Since the nature of gravitation is to be extremely weak compared to the other 3 basic forces in our universe, gravitational waves cause only very small distortions in space-time and proofed to be very hard to detect, as in addition their interaction with matter is basically zero [4]. Therefore, only the most extreme objects in the universe known to us may produce waves large enough for us to detect them. Hence, the gravitational wave detectors have been constructed with a main focus of binary Black-Hole (BBH) and binary Neutron-Star (BNS) mergers [5].

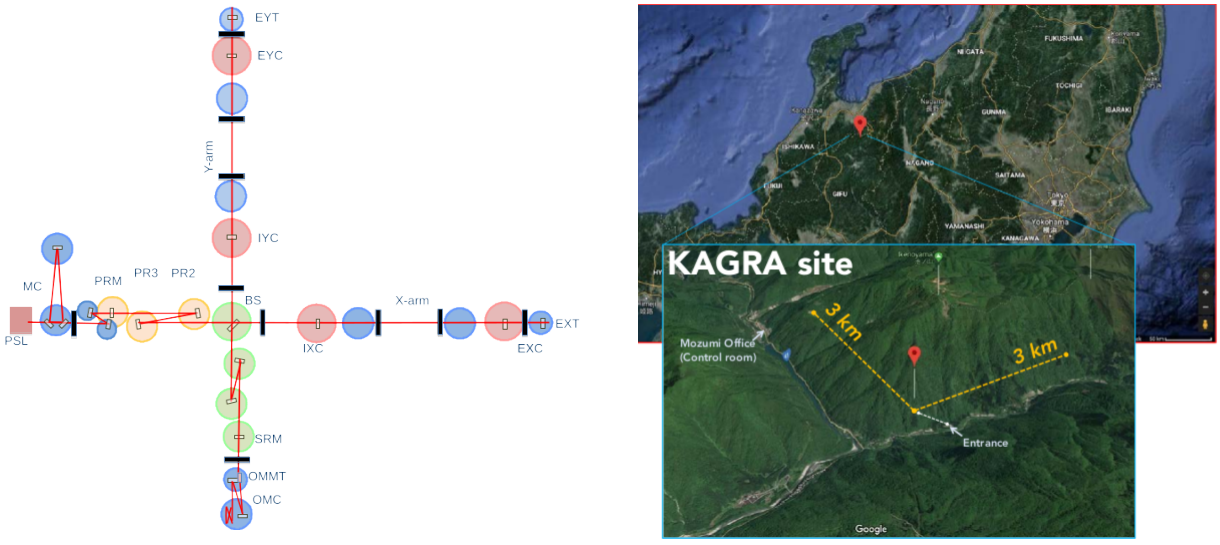

Figure 1: KAGRA is a Fabry-Perrot-Michelson interferometer with an arm length of each 3km built inside the Ikeno mountain in the Gifu prefecture of Japan. On the left, the basic optical layout is shown while on the right, its geographic position and orientation is given.

In order to achieve the necessary sensitivities to detect such events, laser-interferometry has been shown to be most efficient. Indeed, in 2015, the very first direct detection of gravitational-waves has been achieved by the LIGO detectors That detection originated from a BBH merger 410 Mpc away [6]. Hence, also KAGRA uses the Fabry-Perrot-Michelson interferometer technique with a cavity-length of 3km (see Fig. 1), using a polarized 1064nm laser beam to detect length differences in both interferometer arms. While LIGO and Virgo are operated at room-temperature, KAGRA cools its 4 main mirrors which are given in Fig. 1 as IXC, IYC, EXC, and EYC

(henceforth called test-masses) down to around 20K. Such cryogenic cooled optics require more efforts to be operated but its benefit is a less thermal-noise injection which is generally a limitation at gravitational wave frequencies around 10 - 100Hz in terms of sensitivity [1]. Due to its higher thermal conductivity at low temperatures, KAGRA is using Sapphire as the bulk material for the dielectric coated test-masses. Sapphire is a crystalline form of Al_2O_3 and its unit-cell has two axes with different refraction indices. That makes Sapphire a cause of birefringence, which means that light passing through the crystal and facing both axes changes its polarization. Therefore, all test-masses are produced with the crystallographic c-axis being parallel to the optical axis of the laser beam. Small distortions of the crystal lattice, however, due to internal stress which has its origin in the manufacturing process, can introduce unwanted birefringence effects [7] which alter the polarization of the laser and hence the sensitivity of the detector. Such unwanted effects need to characterized for further improvements in Sapphire substrate manufacturing and particularly future upgrades of KAGRA.

2. Measurement System

In TAMA300 we have already established a measurement system to acquire the absorption coefficient distribution of high-quality optics as 3D maps, spatially resolved down to 0.1x0.1x1mm, which we are using already to characterize optics for the harsh constraints of KAGRA in terms of absorption (see the contribution of Pengbo Li in this proceedings for further details and M. Marchio's Ph.D. thesis [8]). That system is based on the Photo-thermal Common-path Interferometer technique where a pump beam is used to trigger internal absorption and a probe beam to detect it.

We have configured the PCI system to use only the polarized pump-beam to measure the birefringence effect of Sapphire samples which have been produced for KAGRA or which are samples from companies to be characterized for future upgrades of KAGRA.

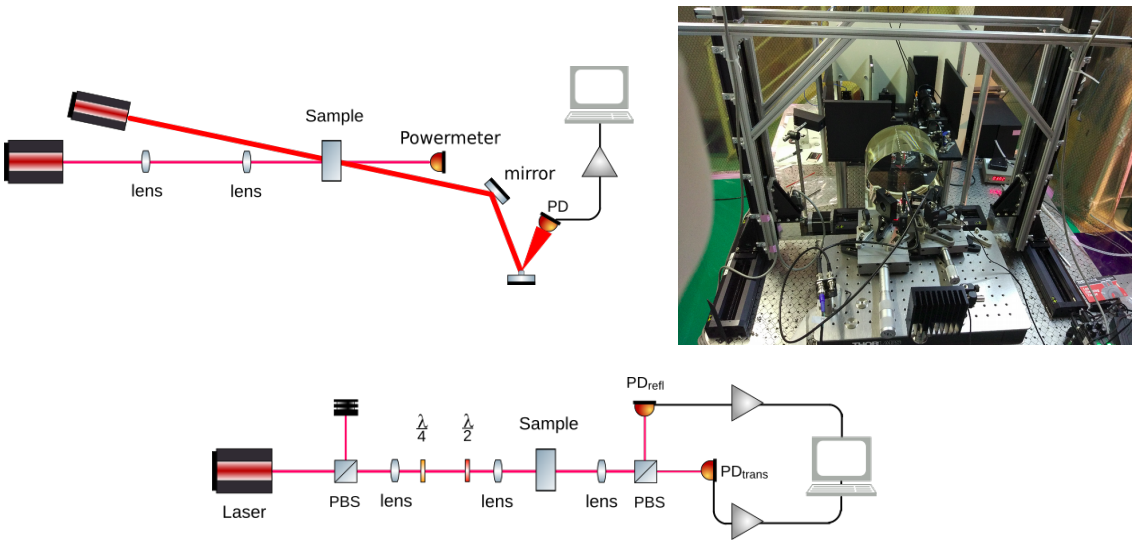

Figure 2: top: layout and photograph of the PCI before the reconfiguration. As can be seen, we are using 2 laser-beams for the absorption measurements. In the photo, the PD and the powermeter are on the bottom with a KAGRA-sized Sapphire sample in the sample-holder.
bottom: the optical layout after the reconfiguration to measure birefringence.

In Fig. 2, you can see a basic outline of the PCI and a photo of it with a KAGRA-sized Sapphire substrate mounted on the translation-stage which is used to move the sample from measurement-point to measurement point. The test-masses are cylindrical with a diameter of 220mm and a thickness of 150mm. The optical layout has been changed to be more polarization sensitive for the incoming pump-beam and to be able to divide the out-coming beam into S and P polarized parts (with respect to the optical table). We are using photodiodes for the detection of each part and define the polarization angle as a measure for the birefringence properties of the sample to be

$$\theta = \arctan\sqrt{\frac{P_S}{P_P}}$$

where P_S and P_P is the power of the S and P polarized beams, detected by the photodiodes.

Since we are using only one beam, we cannot produce 3D maps like we are doing in absorption but only 2D maps. The largest beam-diameter achievable is about 0.5mm. Hence, we are limited in the spatial resolution of the birefringence maps to that value in both lateral and vertical direction (with respect to the beam). For the KAGRA-sized samples, however, we took the maps with a resolution of 1x1mm to limit the measurement time to 9h for

each map (for one spot, we need approximately 3s of measuring time).

3. Results

We have taken birefringence maps from 4 KAGRA-sized substrates (2 from the company “Shinkosha” and 2 from the company “GT”) and 2 TAMA-sized ones (diameter 100mm, thickness 50mm), both from Shinkosha. In addition, we have characterized several smaller sized samples from Shinkosha. But, they are not discussed here.

In Fig. 3, the basic outcome of the measurements on one of the KAGRA-sized substrates (which is actually a spare substrate that does not fulfill all the requirements for KAGRA) is shown together with its respective 2D absorption map, taken in the center of the bulk. Beside the obvious inhomogeneity of the polarization angle and therefore the birefringence in this sample, the correlation between absorption and birefringence pattern is astonishing.

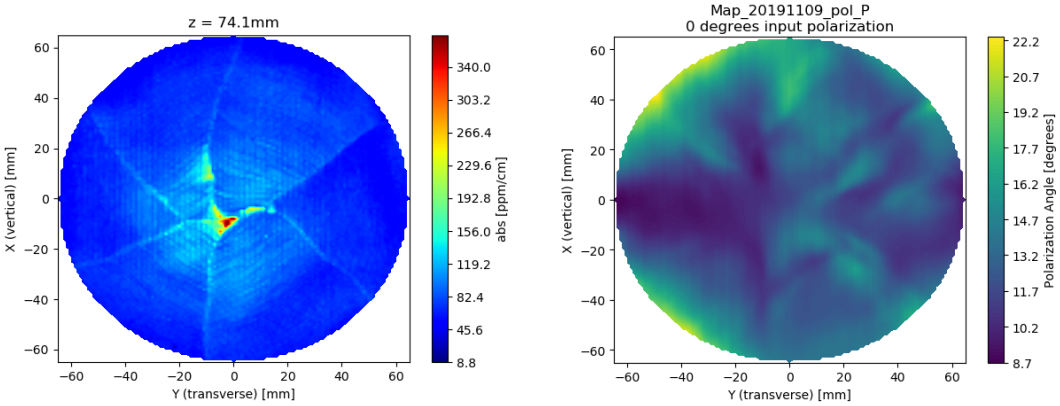

Figure 3: on the left the absorption coefficient distribution of a KAGRA-sized Shinkosha substrate is shown, taken at the central position of the cylinder axis. On the right, the birefringence map through the whole cylinder is presented. The position of both maps is equivalent.

The hexagonal structure in the absorption map may be visible also in the birefringence map. Please note that in both cases the X and Y axis show equivalent positions in the 2D projection of the cylinder. The above shown results are from one sample coming from Shinkosha but we have already confirmed that also for other samples from that company similar correlations between absorption and birefringence appear. However, we could show for samples coming from GT, which uses apparently a different method of Sapphire crystallization, that such strong correlations are not the rule. Nevertheless, also for GT we found birefringence patterns.

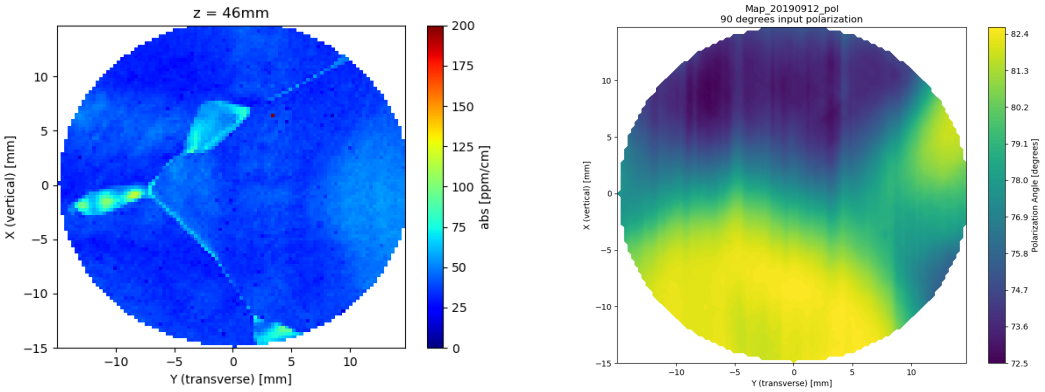

Figure 4: result on the measurements for the smaller TAMA-sized samples. Left: the absorption map, right: the birefringence map.

Given the size of the Sapphire test-masses, it may be obvious to assume that due to manufacturing issues, internal stress appears which cannot be sorted out by cutting. This notion may be right, but even for smaller samples as the TAMA-sized substrates we see in one out of two samples patterns of birefringence correlated to those in absorption which can be seen in Fig. 4. Here, we see a three-fold division in the absorption coefficient distribution which in parts is also visible for the birefringence.

4. Summary and Outlook

With our approach of a direct measurement of birefringence inhomogeneities with the aid of a laser rastering a crystalline sample and creating a 2D map of the polarization-angle distribution, we have established an alternative approach to address inhomogeneities in the refractive index which are the result of lattice distortions of the crystal. Similar results to those which are presented here have been also found with transmitting-wave-error measurements. In the case of our system, however, we can connect those inhomogeneities now to the orientation of the lattice structure.

Nevertheless, our approach is just a first step. Since polarization of light is generally being described as elliptical (with having linear S and P polarizations as special cases), we need information on the orientation of the polarization-ellipse in space to understand the exact phase-shift and hence the changes that happen to the electromagnetic wave inside a sample.
Our next step, therefore, is an upgrade which introduces another half-wave plate in the out-going beam in order rotate the polarization to be always maximized in either S or P. The information will give us then the orientation of the ellipse plus its ellipticity. In addition, we are now improving the incoming beam's polarization to increase the signal/noise ratio of our measurements further.

5. References

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