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Fast birefringence measurement and compensation for KAGRA and future gravitational waves detectors

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To reduce the impact of thermal noises, KAGRA gravitational wave detector is operated at cryogenic temperature. This makes the use of crystalline substrates mandatory since non-crystalline materials have worst performances. Within the KAGRA experiment, the crystalline material of choice is sapphire. Next generation of gravitational wave detectors will also use crystalline substrates, possibly sapphire or silicon. All these materials are birefringent which can spoil both the sensitivity and duty-cycle of the detectors and therefore substrates with lowest possible birefringence are mandatory. Within the KAGRA collaboration, we have two experiments able to measure the birefringence of the 22kg sapphire substrates with a duration of weeks. It is planned to increase the mass of the test-masses to the hundred-kg scale making the current birefringence characterization measurements not realistic to use. Here, we propose to use a pair of identical liquid crystals to measure and compensate birefringence of substrates with arbitrary size. We are now developing such experiment which will decrease the characterization duration by about ten times and possibly down to the second scale for any substrates size. This experiment will also demonstrate the possibility to compensate birefringence in gravitational waves detectors.

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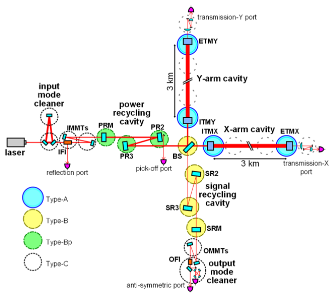
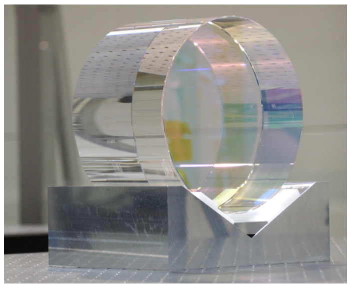
1. Introduction

The first direct detection of gravitational wave (GW) on September 14th 2015 by the LIGO detectors marked the birth of gravitational wave astronomy [1]. Since then, more than 90 GW events have been detected by the LIGO-Virgo collaboration [2]. Among them, the detection of GW emitted by the merger of a binary neutron stars (GW170817) highlighted the importance of GW within the multi-messengers astronomy as the GW sky localization allowed a prompt follow up campaign from numerous observatories [3]. This good sky localization was thanks to the triple detectors detection. Since May 24th 2023, the fourth observation run O4 started. It will be the first time that four kilometric-size GW detectors are operating together with KAGRA joining the LIGO-Virgo collaboration. KAGRA is often referred as a 2.5th-generation GW detector as, in addition to design and scale similar to LIGO and Virgo detectors (2nd-generation), it is operating underground with test-masses at cryogenic temperature [4]. At such temperature, the use of fused silica is not possible due to poor thermal and mechanical performances. Therefore, KAGRA is using Sapphire test-masses. The next generation of GW detectors such as Einstein Telescope or Cosmic Voyager will also operate at cryogenic temperature and therefore use crystalline test-masses (current candidates being Sapphire or Silicon). One major challenge of such crystalline material is the presence of non-uniform birefringence which can limit both the duty-cycle and sensitivity of GW detectors [5]. It is therefore mandatory to develop birefringence measurement experiment to select the crystalline bulk with lower and uniform birefringence. Here, we propose a birefringence measurement method that will allow drastic measurement duration reduction as well as being able to fully compensate birefringence.



(a) Simplified optical scheme of KAGRA from [4]



(b) A KAGRA test-mass

Figure 1: KAGRA scheme and one of its test-masses

2. KAGRA detector and birefringence

The GW detector KAGRA is a Power-Recycled Fabry-Perot Michelson as shown in figure 1a. The four test-masses forming the X- and Y-arm cavities are 23 kg Sapphire of 22cm diameter and 15cm thickness as shown in picture 3b.

Sapphire is hexagonal crystalline form of Al_2O_3 where the oxygen and aluminium atoms are so that it forms a uni-axial crystal [6]. For such crystal, there is an axis (here called the c-axis) for which a linearly polarized light propagation will keep the same polarization. When

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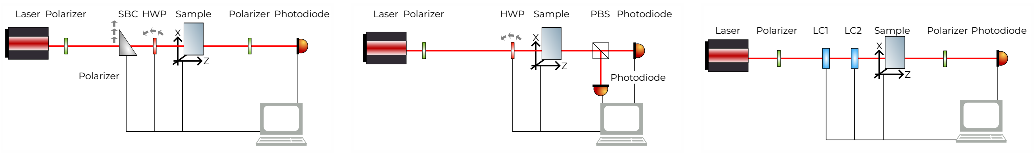

(a) Soleil-Babinet Compensator and rotating Half-Wave Plate

(b) Linear polariscope

(c) Liquid Crystal based birefringence measurement

Figure 2: Simplified optical schemes of the birefringence measurements within KAGRA collaboration.

manufacturing KAGRA test-masses, the Sapphire is therefore oriented so that its c-axis matches the light propagation direction. However, both misalignment of the test-masses or the optical beam as well as imperfect growth can lead to non-uniform birefringence of KAGRA sapphire test-masses.

This means that the birefringence is directly affecting the optical beams circulating in the arms and therefore affecting the ability to detect GW signals.

Indeed, KAGRA is designed to operate with S-polarization; meaning that all the optical components of KAGRA have optimised performances in this polarization. Sapphire birefringence is causing part of the circulating beam to be converted into P-polarization. This component will see optical components with non-optimal parameters. Furthermore, S- and P-polarization form an orthogonal basis making them not interfere together. As the GW signal and several interferometer control signals are coming from the interference between the beams circulating in each arm cavities, their signal-to-noise ratio are affected by test-masses birefringence [5].

3. Current birefringence measurements

Birefringence of a material is inducing polarization rotation and retardation. The goal of birefringence measurement setup is therefore to measure both these parameters.

There are currently two experiments to measure sapphire birefringence within KAGRA collaboration.

The first experiment uses a Soleil-Babinet Compensator (SBC) and a rotating Half-Wave Plate (HWP) placed between crossed polarizers [7] as shown in figure 2a. A SBC is composed of birefringent materials with variable thicknesses. It can therefore act as a variable polarization retarder depending on the SBC translation orthogonal to the beam propagation. The rotating HWP is used as a variable polarization rotator where the polarization rotation is twice the rotation angle of the HWP.

Without any sample installed, no light is transmitted owing to the cross polarizers configuration and proper tuning of the SBC and HWP. When placing a birefringent sample between the crossed polarizers, part of the light will be projected onto the output polarizer axis and some light will be transmitted. By translating the SBC and rotating the HWP, it is then possible to extinguish the transmitted light. At that point, the polarization retardation and rotation respectively induced by the SBC and HWP are exactly compensating the sample birefringence. This method is therefore a direct measurement of birefringence.

A second setup is a linear polariscope where several measurement of S- and P-polarized components of the transmitted light are performed with various rotated linear polarized light at the

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input [8]. Before the sample, a linear polarization is incident on a HWP which rotation angle is remotely controllable as shown in figure 2b. The light transmitted by the sample is then divided into its S- and P-polarization components by a Polarizing Beam Splitter (PBS). By performing several measurements with various input polarization rotation, it is then possible to reconstruct the sample birefringence.

The sample retardation is often described by the coefficient Δn that represents the difference between the ordinary and extra-ordinary refractive indexes. Both these experiments reaches about 1 to $2{\cdot}10^{-9}$, far below the level of current KAGRA test-masses [7][8]. By placing the measured sample on a 3D translation stage, it is then possible to achieve 2D measurement of the birefringence across the sample surface by moving the sample around the optical beam. Due to the heavy mass of KAGRA sample, it is not possible to move it too quickly which limits the measurement speed to about 1 to 2 Hz. Furthermore, the linear polariscope method requires at least 2 measurements but we typically combine 6 to improve statistics. This leads to a final measurement speed of about 0.17 Hz. For the SBC technique, it is required to scan a large space parameters leading to a measurement speed of about 0.03 Hz.

This means that at least 2 weeks are required to characterize one KAGRA-size sample. For future KAGRA upgrades and future generation of GW detectors, it is planned to use 100 kg-scale test-masses making the choice of such test-masses possibly lasting several years due to slow mechanical motions.

In the following, we propose a new birefringence measurement setup that is not using any mechanical motions so to decrease the measurement duration to the second level for arbitrary sized samples. At its heart, this experiment will use Liquid Crystal (LC) as both polarization retarder and rotator.

4. Liquid crystals as polarization states generator

Liquid crystal were first discovered at the end of the 19th century. In the following decades, several kinds of LC were discovered and their effects on polarization as a function of applied electrical and magnetic fields were studied [9]. Their use as Liquid Crystal Display (LCD) made them go from scientific curiosity to a huge industry and use in various fields of research.

LC used here (LC1111-TC, Thorlabs) are composed of birefringent rod-like molecules contained inside a transparent cell sandwiched between electrodes. Without any voltage applied, the LC molecules are aligned following the alignment layer. Applying voltage to the LC cell, the LC molecules tilt and follow the electrical field. It means that LC cell acts as a electrical variable polarization retarder. In order to minimize alignment drifts of the LC molecules, the applied electric field amplitude is square-modulated. The typical switching frequency of LC is about 100 Hz. This is one of the main advantage of LC with respect to the motion variable polarization retarder previously mentioned.

By using a pair of such LC cell, it is actually possible to achieve both polarization rotation and retardation. More precisely, the first LC (LC1) fast-axis has to be oriented at 45deg from the input linear polarization direction and the second one (LC2) has to be a 0deg. Using the Jones formalism [10], a perfect LC with its fast axis at an angle θ from the input polarization direction and retardation $\epsilon(V)$ where V is the applied electric field is described by :

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$$T_{LC}(\epsilon,\theta) = R(\theta)\cdot\begin{pmatrix} e^{-i\epsilon/2} & 0 \\ 0 & e^{i\epsilon/2}\end{pmatrix}\cdot R(-\theta) \text{ with } R(\theta) = \begin{pmatrix}\cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta)\end{pmatrix} \tag{1}$$

The effect of the pair of LC on a linear polarized light is then :

$$J_{out} = T_{LC}(\epsilon_2, 0)\cdot T_{LC}(\epsilon_1, 45)\cdot\begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}\cos(\epsilon_1/2)\cdot e^{-i\epsilon_2/2} \\ i\sin(\epsilon_1/2)\cdot e^{i\epsilon_2/2}\end{pmatrix} \tag{2}$$

This shows that LC1 acts as a polarization rotator while LC2 acts as a polarization retarder. This approach is already used in biology to measure living cells birefringence [11] but has never been used to measure birefringence of large sample such as needed for the GW detectors.

4.1 Liquid Crystal calibration

In order to use a pair of LC, it is then necessary to calibrate the LC retardation as a function of applied electric field and precisely measure its fast-axis direction.

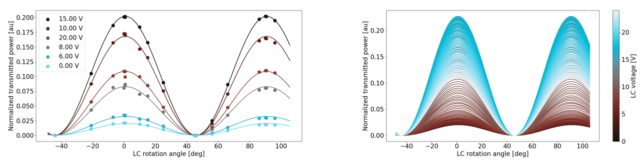
To perform all the calibration and measurements steps, we automated most of the measurements using LabView. We achieved up to 80Hz measurement speed (more than 100 to 10 times faster than previous methods).

We install the LC between cross-polarizers with two power-meter respectively measuring the input and output power. The voltage applied to the LC is varied between 0 to 25V with 1mV resolution. This LC is mounted on a motorized rotator.

We measured the transmitted power normalized by the input power to get rid of input power fluctuations. It can be fitted as a function of it rotation angle θ by :

$$P(\theta) = A\cdot\cos\left(2(\theta-\theta_0)\right)^2 \tag{3}$$

where A is the power gain and θ_0 the orientation of the LC fast-axis with respect to the input polarization direction.



(a) Some measured voltages. Dots are measured data and plain lines are fit.

(b) All fitting results.

Figure 3: Normalized transmitted power while varying the voltage applied to LC1 and rotating it.

This is shown in figure 3 for LC1 where its applied voltage was changed between 0 to 25V with 1mV increment and rotated over more than one period.

As the transmitted power is minimal when the LC fast-axis is aligned with input polarization ($\theta = \theta_0$) and maximal when it is oriented at 45deg, we could estimate the LC1 fast-axis to be aligned with our input polarization direction when it was rotated to 45.74 deg. This estimation was limited by the resolution of our rotation controller (Thorlabs PRM1).

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This allows for a precise estimation of the LC fast-axis orientation. Indeed, we simulated the expected power variation as a function of the voltage applied to the LC. It can be seen that at 0V, where the retardation is minimum, the retardation tends to 532 nm (half-wave). In our experiment, we measured retardation of about 539 nm which corresponds to a misalignment of the LC fast-axis of less then 0.01 deg.

We can then reconstruct the LC retardation from the normalized transmitted power as a function of applied voltage when $\theta - \theta_0 = 45$ deg (ie its maximum retardation).

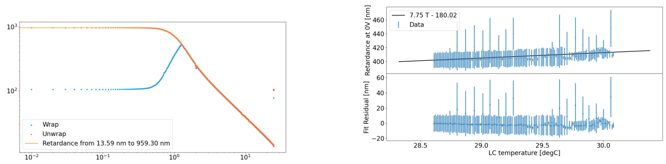
In order to compute the retardance R in nm from the normalized transmitted power P, we used the following equation :

$$R = \frac{\arcsin(\sqrt{P})}{\pi\lambda} \tag{4}$$

where λ is the wavelength of the laser in nm.

Finally, it is needed to unwrap R as it is not possible to measure retardance above 532 nm with the cross-polarizers configuration. To do so, we used $R = 2 \cdot \max(R) - R$ for the values where the voltage is smaller than the voltage where the retardance is maximum.

This is shown in figure 4a. The measured retardation is in agreement with the expected value from the manufacturer.



(a) Retardance of LC2 with fast-axis at 45deg from the input polarization direction

(b) Retardance as a function of LC2 temperature

Figure 4: LC2 calibration : Measurement of its retardance as a function of voltage and temperature.

The viscosity of the LC being temperature dependent, the achievable retardation changes as a function of temperature. We are therefore operating our LC at 30 degC with heater based temperature control. The typical temperature fluctuations observed over several days is below 0.1 degC.

We measured LC retardance at fixed voltage while varying its temperature. This LC retardation variation as a function of its temperature follows a linear relation at temperature below 40 degC. Especially, we focused on the temperature range between 29 to 30 degC which is already 20 times larger than the fluctuations we can observe. From our linear fit, we can see that the retardation will change by 7.75 nm/degC.

In the end, we performed these calibrations for both our LCs.

4.2 Arbitrary polarization states generation

Finally, we installed our 2 LCs as described previously and shown in figure 2c : LC1 fast-axis at 45deg of the input polarization and LC2 fast-axis at 0 deg of the input polarization direction. We removed the output polarizers and install a polarization-sensitive camera (Thorlabs, PAX1000-IR2)

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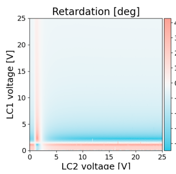
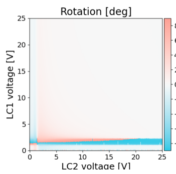
to monitor the generated polarization rotation and retardation as a function of the voltages applied to each LC.

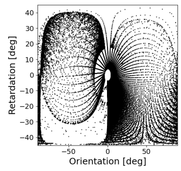
We scanned LC1 and LC2 voltages from 0 to 25V with 0.05V step as shown in figures figs. 5a–5c and over a smaller range but with smaller step (0.01V) in figures figs. 5d–5f Note that due to time constraint we could not perform yet the measurement from 0 to 25V with 0.01V increment. Nevertheless, it is possible to see that most of the polarization space is covered.



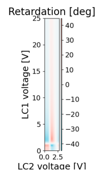
(a) Retardation with 0.05V step



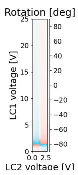
(b) Rotation with 0.05V step



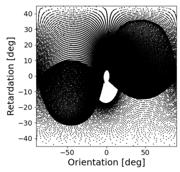
(c) Polarization states with 0.05V step



(d) Retardation with 0.01V step



(e) Rotation with 0.01V step



(f) Polarization states with 0.01V step

Figure 5: Generating arbitrary polarization states with a pair of LCs

5. Future plans

As we are now able to generate arbitrary polarization states at high-speed, we plan to measure and compensate birefringence of samples.

For the birefringence measurement, we plan to investigate various method, from linear polariscope to rotating HWP or Stokes polarimeter. Compared to the compensation method, it should allow for a drastically faster measurement duration; with the aim of seconds duration.

For the compensation, we plan to scan LC1 and LC2 voltages using a Lissajous pattern. This would allow a good coverage of the polarization space without loosing to much speed. The analysis will be similar to the SBC method. It should be noted that it is to our knowledge the first time that birefringence compensation will be applied for GW detectors.

Finally, we plan to upgrade this setup by using a CCD camera readout and substitute the two LC with LC arrays (for instance from LCD) to allow fast 2D birefringence measurement and compensation.

6. Conclusion

Birefringence is already an issue for GW detector using crystalline substrates such as KAGRA. As future GW detectors will also operate at cryogenic temperature, this issue could also limit their performances.

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Using a pair of LCs, we are able to generate arbitrary polarization states up to 100 times faster than previous methods within KAGRA collaboration. This will allow for fast birefringence measurement and open the door for birefringence compensation in 2D for current and future GW detectors.

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