KAGRA

INSTRUMENTS SUMMARY

KAGRA photon calibrator

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February 12, 2017

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Abstract

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Chapter 1

Introduction

1.1 Calibration of KAGRA

1.2 Requirement of KAGRA

1.3 Schedule of KAGRA

Chapter 2

Photon calibrator

2.1 Photon calibrator

One of the goals of the gravitational wave experiment is the accurate measurement of the gravitational waveform that is measured through the absolute displacement of the end test masses. A recent study that LIGO conducted in US showed that a displacement uncertainty could be controlled by the photon calibrator. The photon calibrator is one of the calibration tools to push the mirror surface using the photon pressure of the laser as shown in Fig XXX. The absolute displacement is described as

$$dx = \frac{P\cos\theta}{c} s(f) \left(1 + \frac{I}{M}\vec{a}\cdot\vec{b}\right), \tag{2.1}$$

where P is an absolute power of the laser, c is the speed of light, θ is an incident angle of the laser, I and M are moment of inertia and mass of test mass, $\vec{a}$ and $\vec{b}$ is position vector of photon calibrator lasers and interferometer laser. Then, $s(f)$ is transfer function of the test masses. We simulated the transfer function of test mass as shown in Fig. XXX. We assumed the masses, shapes and Young's modules of the each pendulum mass and fiber as shown in Fig.XXX. According to transfer function, we can regard the motion of high frequency as free mass due to higher than the natural frequency. Therefore, we are able to assume as follows:

$$s(f) = \frac{1}{M\omega^2}, \tag{2.2}$$

where ω is the angular frequency of test mass.

2.2 Purpose of photon calibrator

2.2.1 Interferometer Calibration

2.2.2 Hardware injection test

2.2.3 Photon pressure actuator

2.3 Calibration line of KAGRA

Chapter 3

Instruments overview

3.1 Layout of Photon calibrator

The KAGRA photon calibrator is placed around EXA/EYA chamber, which is installed 36 m away from the end test mass (ETM). We push the mirror surface with the modulated photon pressure directly. Figure 3.1 shows the layout of the KAGRA photon calibrator. The photon calibrator consists of transmitter module (Tx module), receiver module (Rx module), periscope, and telephoto camera module (TCam module). We place the 20 W laser in Tx module, whose frequency is 1047 nm. The 1064 nm laser is not used due to avoid the coupling with main beams. The power of the laser is modulated by the optical follower servo (OFS). We split the beams in Tx module for pushing the drum head node points of the ETM due to elastic deformation. We transfer the beams to the ETM though the periscope. All the periscope structures are placed into the EXA/EYA chamber. The beam is received by the Rx module. We place a 6 inches integrating sphere for the accurate measurement of the laser power and two quadrant photo detector (QPD) for the beam position monitor. We also measure the beam position on the ETM surface using the telephoto camera (TCam). The Tcam is consists of the astronomical telescope, focuser, and high resolution digital camera. Details of instruments are described following section.

3.2 Transmitter (Tx) module

The Tx module is placed at the side of the EXA/EYA chamber. Figure 3.2 shows the view of Transmitter module. All the optical components are mounted on the $900\ \mathrm{mm} \times 900\ \mathrm{mm}$ breadboard (B9090L; Thorlabs). The bread board is placed on the support structure. The electrical module for the control and readout are also hosed in the support structure.

Figure 3.3 shows the optical layout of Tx module. All the optical components are listed in Table 3.1.

TABLE 3.1: .

#	Name	Type
1	Fiber laser	CYFL-TERA-20-LP-1047-AM1-RGO-OM1-T305-C1

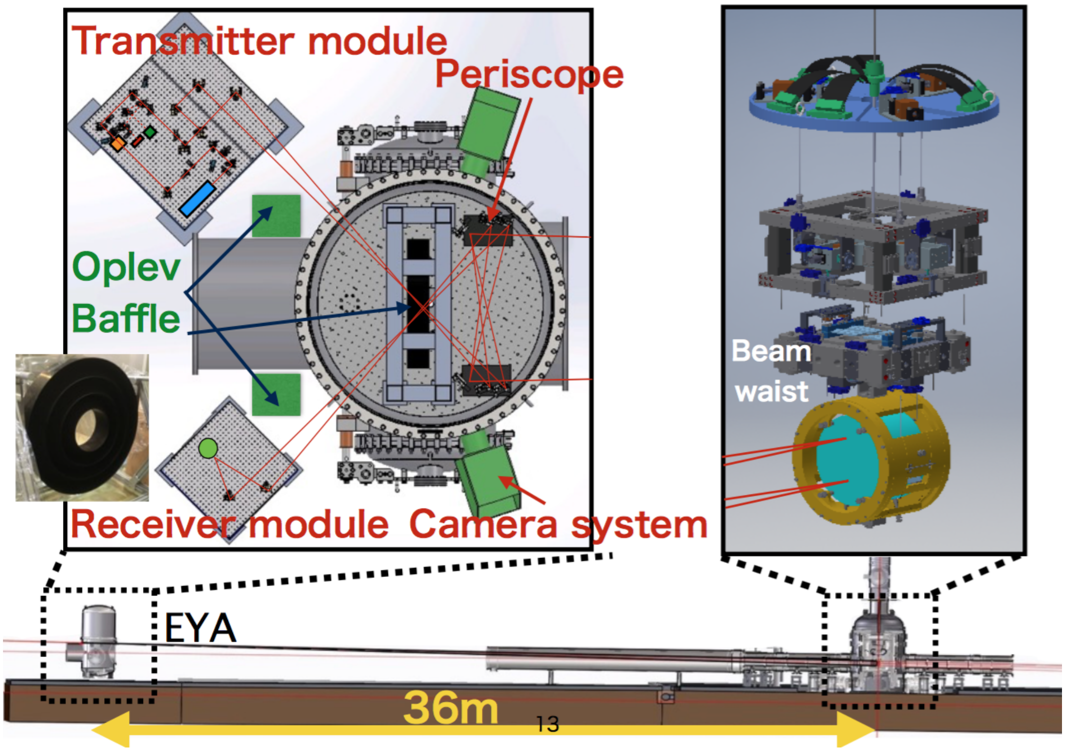

FIGURE 3.1: KAGRA photon calibrator. The calibration system is placed around the EXA/EYA chamber. We mount the optical lever and optical baffle as well.

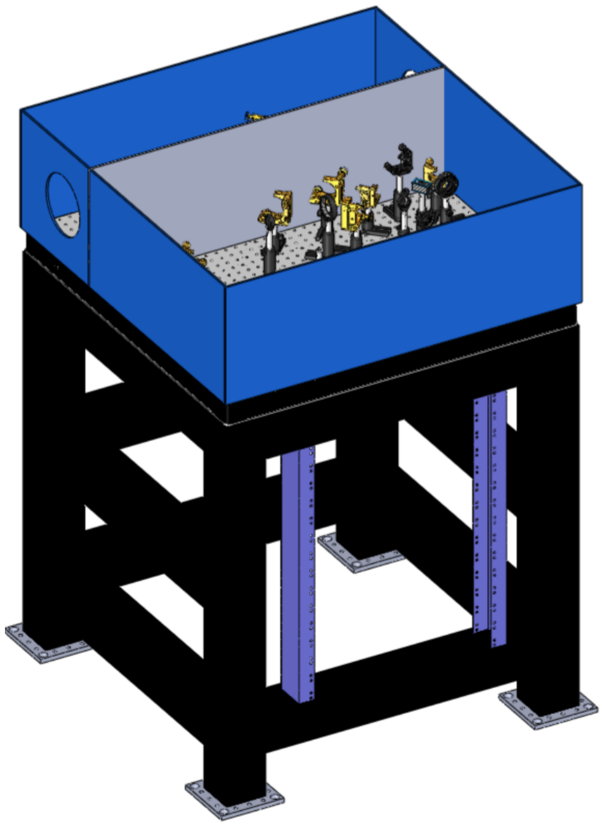

FIGURE 3.2: .

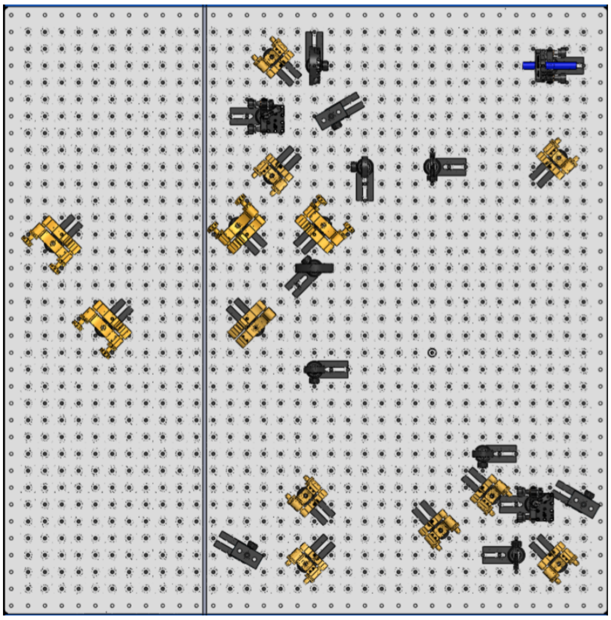

FIGURE 3.3: .

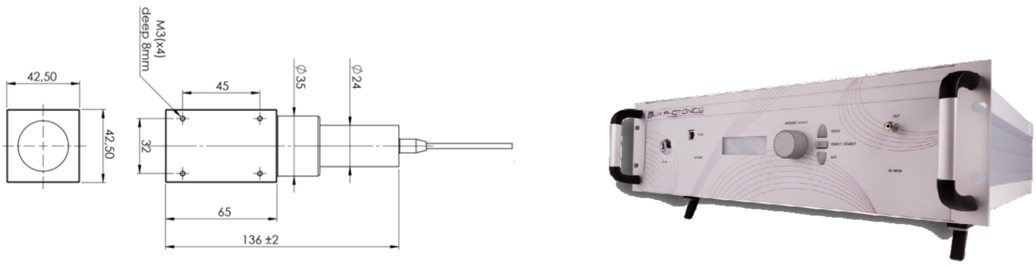

FIGURE 3.4: The fiber laser and drawing of isolator.

3.2.1 Fiber laser

We employ the CW fiber laser made by the LER photonics as shown in Fig. 3.4. The maximum power and frequency are 20 W and 1047 nm, respectively. The model number of the laser is CYFL-TERA-20-LP-1047-AM1-RGO-OM1-T305-C1. The maximum laser power of KAGRA Pcal is 10 times larger than that of LIGO. This is because that we need the high power laser for the injection test and photon pressure actuator technique. The typical beam width of the laser is 0.5 mm when we mount the isolator. We summarize the specification of the laser as shown in Table 3.2.

3.2.2 Beam shutter

We have to pay attention to safety for the operation of the high power laser. In order to dump the beam, we use the beam shutter made by lasermet company. The model number of the shutter is LS-10-12. The aperture size and Max laser power are 15 mm and 20 W. These number meet our requirement due to the laser spot size and maximum power. We control the beam shutter on the GUI. The specification of the beam shutter is shown in Table. 3.3.

TABLE 3.2: Specification summary of CW fiber Laser.

Charactaristic	Typical value	Unit	Note
Operating central wavelength	1047	nm	± 1 nm
CW output power	20	W	
Output signal line-width	0.5	nm	FWHM
Output power stability	± 1	%RMS	Output power: 20 W
Output power tunability	10-100	%	
Optical polarization	Linier		
Polarization extinction ratio	15	dB	
Output fiber	PLMAFUD3460		Nufurn company
Output fiber length	2	m	
Beam diameter	0.5	mm	with isolator
Beam quality	1.1	M^2	
Control mode	Active current control, Active power control		
Beam quality	1.1	M^2	
Supply voltage	84-264	V	AC 47 to 63 Hz
Power consumption	650	W	
Housing	448x451x132.5	mm	
Total weight	13	kg	
Cooling	Air cooled with fans		
Operating temperature	15-35		
Humidity	5-85	%	

TABLE 3.3: Specification of beam shutter.

Charactaristic	Typical value	Unit	Note
Max laser power	20	W	
Aperture size	15	mm	
Drive voltage	11-14	V DC	
Current consumption	150	mA	
Size	$98 \times 63.5 \times 36$	mm	

TABLE 3.4: Specification of HWP.

Charactaristic	Typical value	Unit	Note
Waveplate Type	Quartz Waveplates		
Wavelength Range	1047	nm	
Retardance	$\lambda/2$		
Clear Aperture	85	%	of diameter
Reflection	0.25	%	
Retardance Tolerance	λ /200 to λ /500		at 23Degree C
Material	Crystal Quartz		
Surface Quality	10-5	scratch-dig	
Waveplate Diameter	12.7	mm	

3.2.3 Half wave plate

To control the polarization angle of incident beam, we employ the zero order half wave plate (HWP) made by the CVI laser optics. The model number of the HWP is QWPO-1047-05-2-R10 whose diameter are 12.7mm. The HWP is mounted on the rotation mount made by Thorlabs. The thick ness are optimized at 1047 nm. The specification of the HWP is listed in Table 3.4.

3.2.4 Polarizer

We place two polarizers to define the polarization angle accurately. This is because that the power of the laser is modulated by acousto-optic modulator (AOM) whose performance strongly depend on the incident polarization angle. One polarizer is placed behind HWP. Another one is placed after AOM. The Polarizer is made by Karl-Lambrecht. We purchased TFPC12-1047 that is optimized at 1047 nm.

3.2.5 Lens

We have dane a mode matching simulation using JamMt. We assumed laser beam to be gaussian distribution. We have to place the focus of the laser at the AOM. Thus, we decide the optimal position and focal length of the 1 inch lens (L1), where the assumed beam waist of the fiber laser and AOM are 0.5 mm and XXX mm, respectively. Furthermore, we place two lenses for placing the focus at the surface of the ETM. We employ the combination of 1 inch negative lens and 2 inch positive lens. The Gaussian beam can describe the following relation:

$$w(z) = \sqrt{(}1+), \tag{3.1}$$

where λ is wavelength of the laser, w_0 is beam waist, z is direction from the focus. We estimate the minimum differential beam spot by changing beam waist because it make the alignment easier. The minimum beam spot is written by

$$\frac{dw(z = 36m)}{dw_0} = 0. \tag{3.2}$$

The estimated beam waist and beam spot is 3.5 mm and 5.5 mm as shown in Fig. XXXX. We also place the lens at the front of the photo detector for the OFS. The

TABLE 3.5: Specification of lenses.

Lens number	part number	Diameter [mm]	Focal length
L1		25.4	
L2		25.4	
L3		25.4	
L4		50.8	

TABLE 3.6: Specification of Mirrors.

Mirror number	part number	Diameter [mm]	Polarization
M-Tx-1		25.4	
M-Tx-2		25.4	
M-Tx-3		25.4	
M-Tx-4		25.4	
M-Tx-5		25.4	
M-Tx-6		25.4	
M-Tx-7		25.4	
M-Tx-8		25.4	
M-Tx-9		25.4	
M-Tx-10		50.8	
M-Tx-11		50.8	
M-Tx-t-1		50.8	
M-Tx-t-2		50.8	
M-Tx-b-1		50.8	

parameters of the simulation results are listed in Table. 3.5. All lenses are made by CVI laser optics. The material of lenses are fused silica. The AR coating is placed at both surface.

3.2.6 Mirror

We employ nine 1 inch mirrors and four 2 inch mirrors. The 1 inch mirror is made by CVI laser optics. They place the HR coating on the surface of mirror. On the other hand, we use the HR coating on the fused silica disc of 2 inch in diameter. The coating and polishing the fused silica is made by Sigma-koki corporation. The reflectance of the mirror is shown in Figure. XXXX. The reflectance of HR coating depends on the incident angle and the polarization angle. We labeled mirrors as M-Tx1 toM-Tx-11, M-Tx-t-1,M-Tx-t-2, and M-Tx-b-1. The specification of mirrors are summarized in Table. **??**. All mirror is aligned with optical mirror mount made by Newport company.

3.2.7 Beam splitter

To reduce the elastic deformation, we separate the beam with the beam splitter made by CVI laser optics. The diameter of the beam splitter is 2 inch. Figure. XXX shows the separation ratio of beam splitter.

3.2.8 Optical follower servo

3.2.9 Photo detector

Cover

InGaAs detector

Electrical Cirkit

3.2.10 beam sampler

3.2.11 2 inch integrating sphere

3.2.12 Structure

The breadboard is placed on the support structure. The material of this structure is SUS 306. This structure can be housed electrical devices, such as driver of the fiber laser, electronics of optical follower servo, and driver of laser shutter. We simulated the resonance frequency using ANSYS. The estimated frequency is XXX Hz.

3.3 Periscope

3.3.1 Geometric optics

3.3.2 View window

One of the serious systematic errors are optical efficiency of the view port. Therefore, we have to reduce the reflectance of view port at least 0.1 %. We employ the fused silica optical window whose diameter and thickness are 100 mm and 0.5 inch. We place the AR coating on both surfaces of the window. Figure XXX shows the simulated transmittance of the view port. The effective diameter of the view port is about 3 inch. The incident angle of the beams are XXXX degree.

The flange type of the view port is ICF152. We remodeled the blank flange of ICF 152 made by Cosmotech. Figure XXX shows the drawing of the view port. We employ the G-85 o-ring for vacuum sealing.

3.3.3 Mirrors

We employ eight 3 inch mirrors. We place the HR coating on the polished fused silica disc. The coating and polishing the fused silica is made by Sigma-koki corporation. The reflectance of the mirror is shown in Figure. XXXX. The reflectance of HR coating depends on the incident angle and the polarization angle. We labeled mirrors as M1, XXXX. The specification of mirrors are summarized in Table.XXXX. All mirror is aligned with optical mirror mount made by XXXXXX.

3.3.4 Structure

3.3.5 Alignment

3.4 Receiver module

3.4.1 6inch Integrating sphere

The 6 inches integrating sphere is used for absolute power measurement of the laser. We receive the laser beam from two paths. To receive the power perfectly, we need

TABLE 3.7: Specification of Mirrors in periscope.

Mirror number	part number	Diameter [mm]	Polarization
M-P-1		76.2	
M-P-2		76.2	
M-P-t-3		76.2	
M-P-t-4		76.2	
M-P-b-3		76.2	
M-P-b-4		76.2	
M-P-5		76.2	
M-P-6		76.2	

a sufficiently large diameter hole of integrating sphere. We use for the 2 inch hole integrating sphere. We mounted the photo detector at the top of port. Details of the photo detector is explained in XXXXX.

3.4.2 Mirror

We employ four 2 inch mirrors. We place the HR coating made by Siguma-koki as shown in Fig. XXXX. For two mirrors, we make the AR coating on the back surface to pick up the beams. The specification of the mirrors are listed in Table 3.7.

3.4.3 QPD

3.4.4 Structure

The breadboard is placed on the support structure. The material of this structure is SUS 306. We simulated the resonance frequency using ANSYS. The estimated frequency is XXX Hz.

3.5 Camera module

The beam position of the ETM surface corresponds to systematic error of the rotation and elastic deformation. To measure the beam position, we measure the mirror surface directly. However, the KAGRA EXA/EYA chambers are placed at 36m far from the ETM. Thus, we employ the combination of telescope and high resolution camera, we call telephoto camera (TCam). We are tuning with focus point of the mirror using focuser. We place the view port and mirror between the ETM and TCam. Figure XXX shows the drawing of TCam unit.

3.5.1 Camera

Purpose of using the high resolution camera, we have to measure the beam position within 1 mm accuracy. Ww solved this problem by D810 digital camera made by Nikon. The D810 reprises the 36-megapixel resolution with 35.9×24.0 mm CMOS sensor. We remove the IR filter because the commercial camera is not sensitive to laser wavelength (1047 nm).

3.5.2 Telescope

We employ the Maksutov-Cassegrain type telescope for observing the ETM surface. The diameter of the primary mirror is 127 mm and its focal length is 1500 mm ($f/12$). The telescope is manufactured by Sky-watcher company. The diameter of the telescope is limited by the that of the view window size.

3.5.3 Focuser

A focuser, which is made by Moonlight, is used for the automatic focus control. We connect focuser between telescope and camera. The model number is XXXXX.

3.5.4 View window

The flange type of the view port is ICF203. We remodeled the blank flange of ICF 203 made by Cosmotech. Figure XXX shows the drawing of the view port. We employ the G-135 o-ring for vacuum sealing.

3.5.5 Mirror

We place the mirror in the EXA/EYA chamber. The mirror size is $100 \times 80mm$, which is mounted on the aluminum holder and optical mount. The mirror is made by Thorlab.The reflectance of the mirror is shown in Fig XXXX.

3.5.6 Illuminator

3.6 Summary

Chapter 4

Elastic deformation

The elastic deformation is one of the serious systematic error in Photon calibrator.

4.1 Free mass motion

4.2 Transfer function

4.3 Modal analysis

4.4 Elastic deformation

4.5 Summary

Chapter 5

Absolute power calibration

5.1 Introduction

This section describes the in-situ calibration procedure of Photon Calibrator at each End station of KAGRA.

5.2 Theory of Operation

The Working Standard referred as WS is an integrating sphere with InGaAs photo detector, which has been calibrated against Gold Standard (GS) in the lab at LHO. The Gold Standard is calibrated by NIST. We will use this working standard to calibrate the Transmitter Module Photo Detector (TxPD) and Receiver Module Photo detector (RxPD), which are inside the Transmitter module and Receiver module of Photon calibrator respectively.

The following formula is used to obtain the calibration factor that will give the response of photodiodes in Photon calibrator modules in Watts/Volts:

$$\mathrm{TxPD} = \frac{\mathrm{TX}}{\mathrm{WS}} * \frac{\mathrm{WS}}{\mathrm{GS}} * \mathrm{GS} \tag{5.1}$$

$$\mathrm{RxPD} = \frac{\mathrm{RX}}{\mathrm{WS}} * \frac{\mathrm{WS}}{\mathrm{GS}} * \mathrm{GS} \tag{5.2}$$

5.3 End-station

5.4 Gold standard

5.5 Working standard

Chapter 6

Beam position monitor

Chapter 7

Summary