Development and Characterization of Optical Follower Servo for Photon Calibrator for KAGRA Gravitational Wave Observation

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Outline

- Overview
- Instruments of Photon Calibrator
- Noise Requirements
- Optical Follower Servo and feedback loop
- Measurement plan
- Results
- Summary

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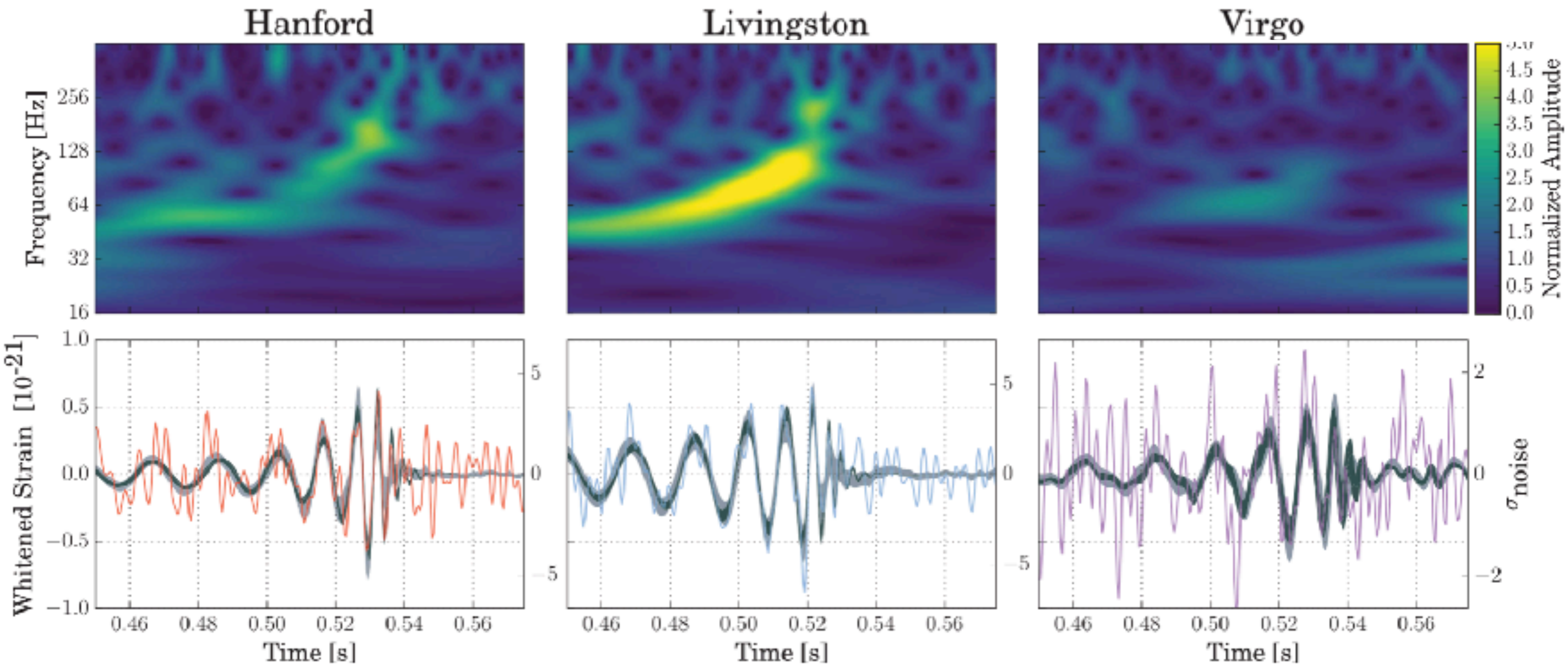
Why Calibration is important?

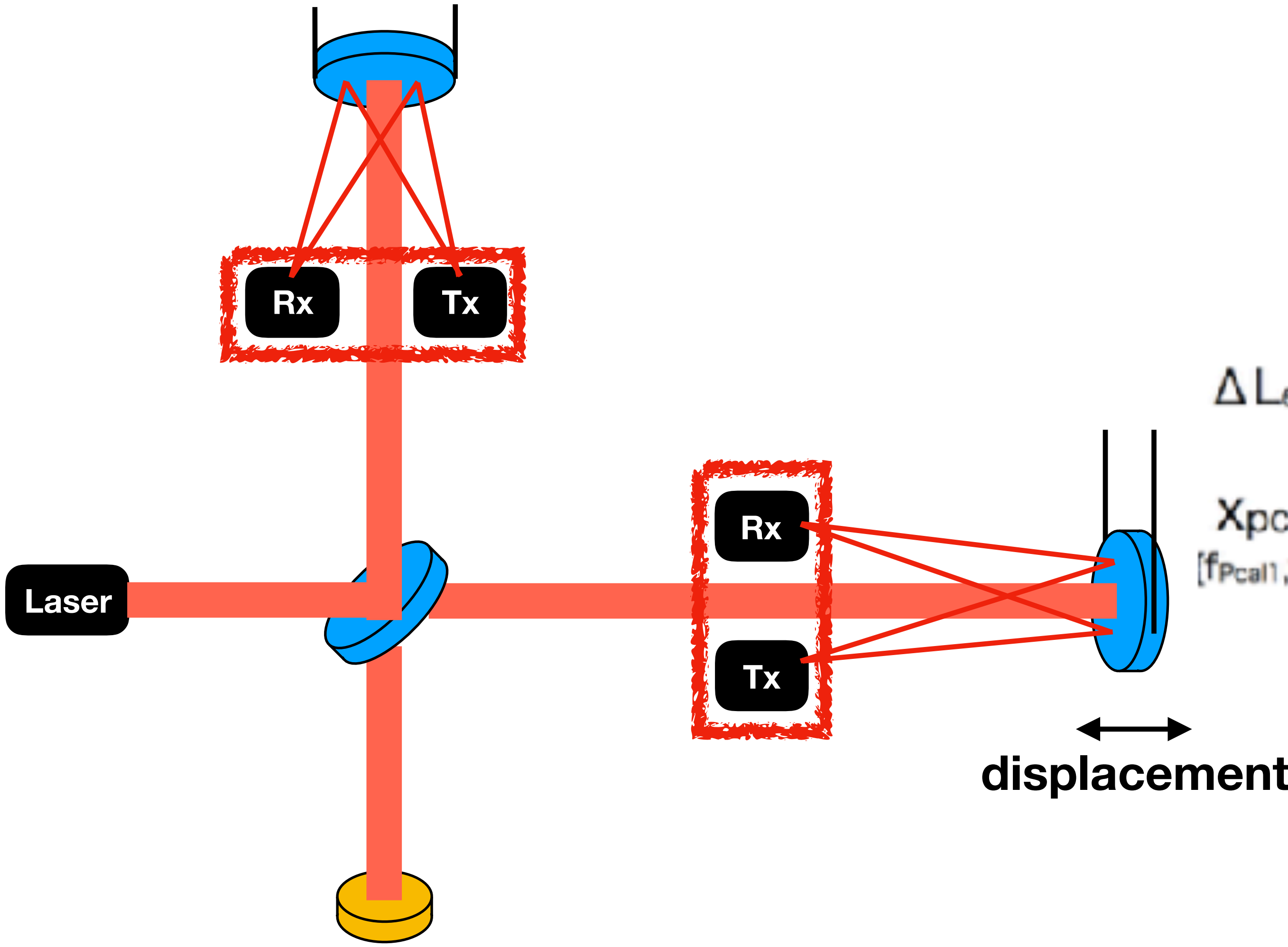


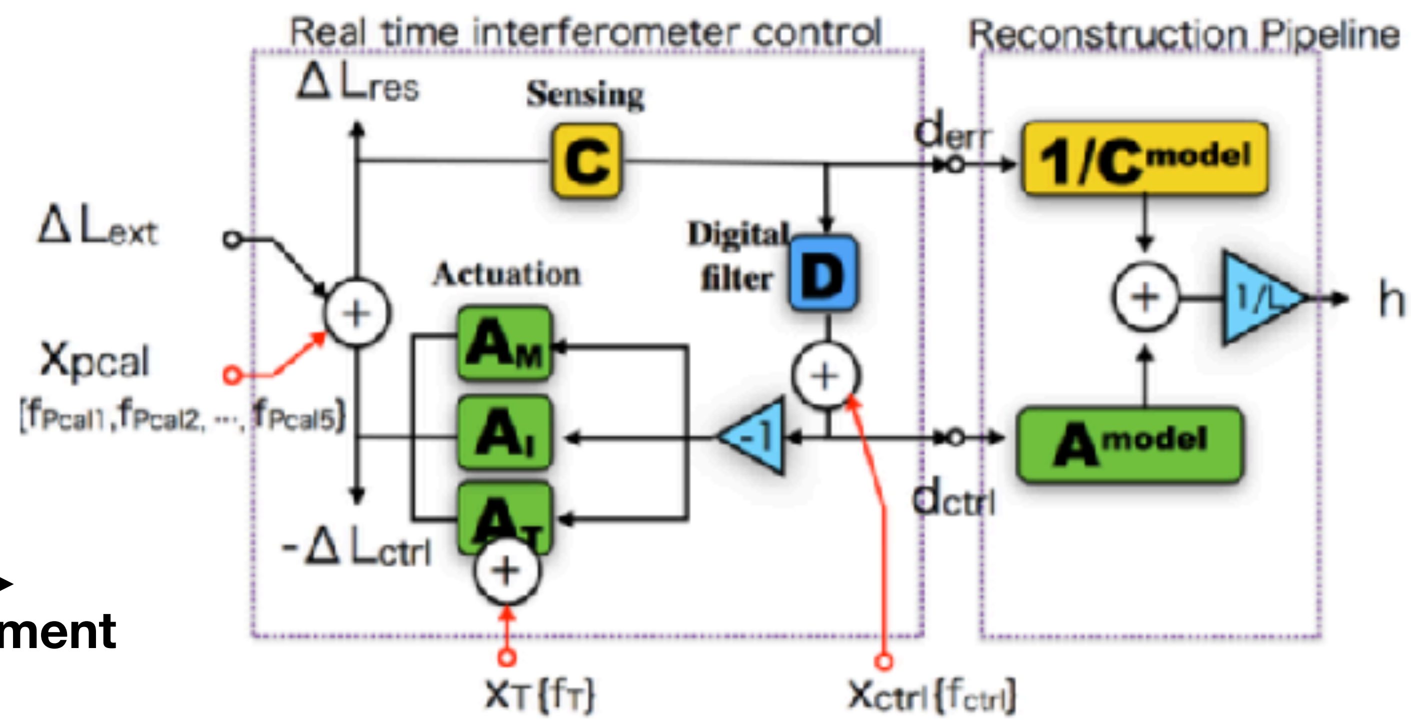
- LIGO and Virgo have already detected gravitational wave, we need the calibration to extract parameters accurately from gravitational wave signal.

Goal of accuracy

- 1% in amplitude
- 1 degree in phase

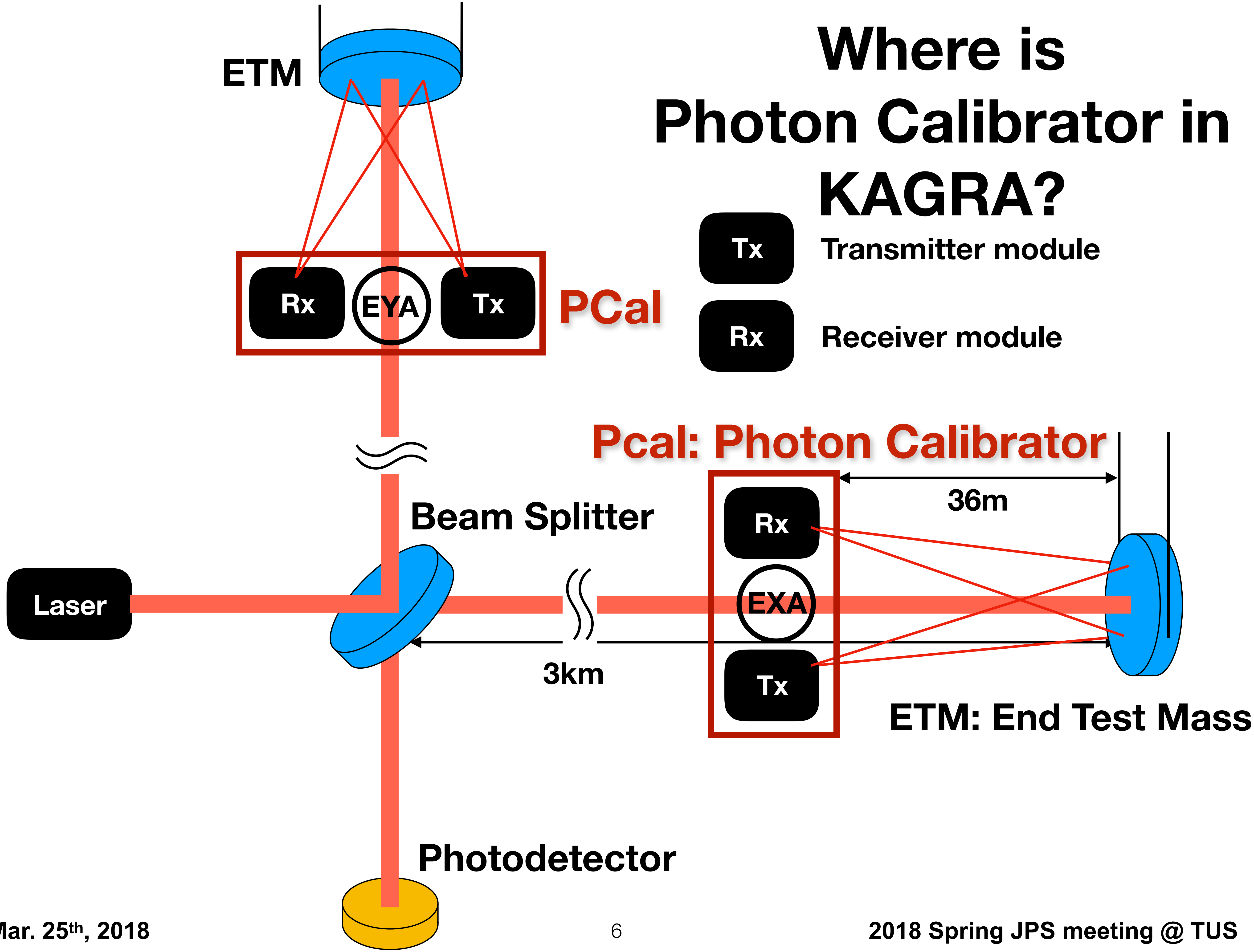
Why we need Photon Calibrator?

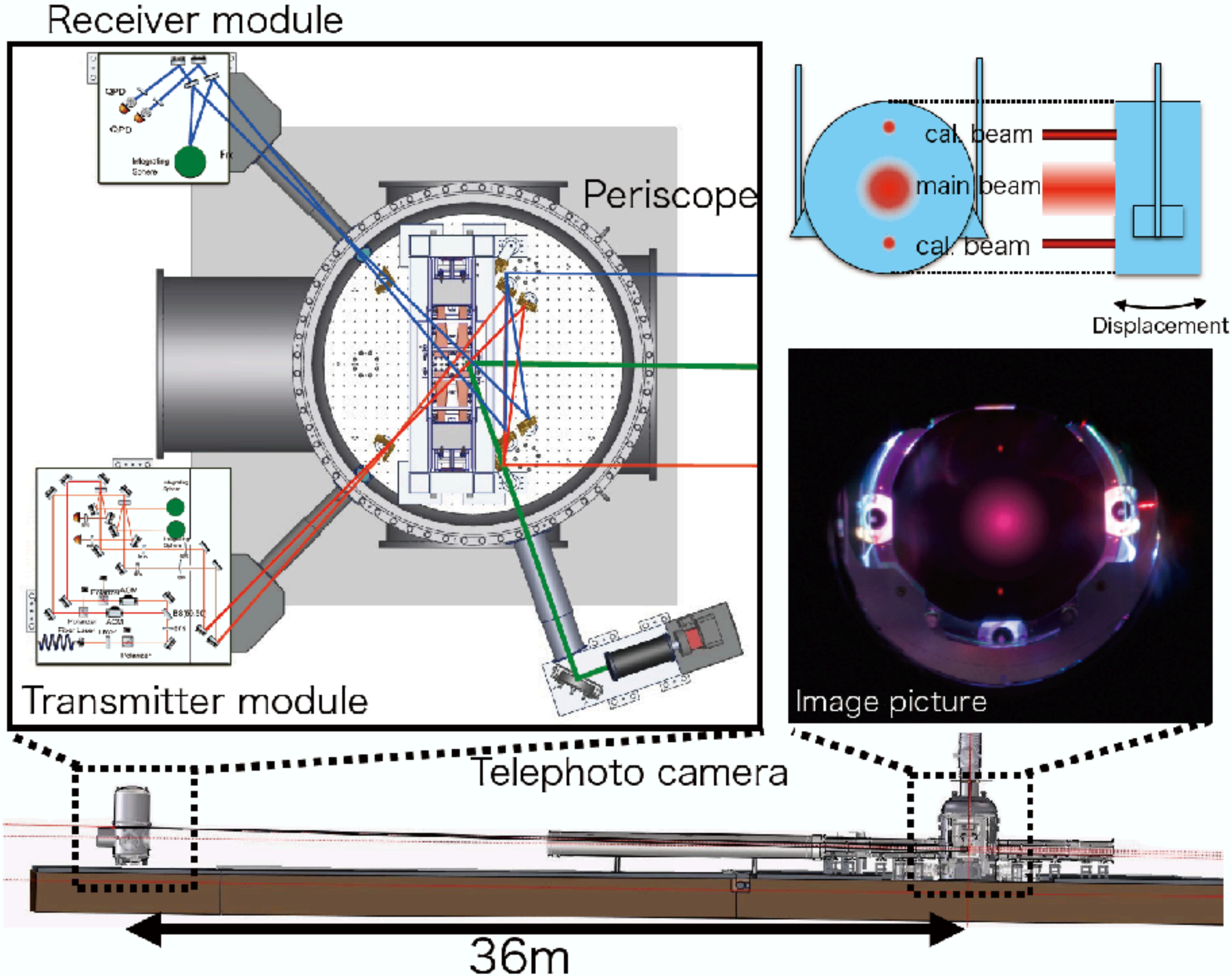




1. Characterize the displacement of mirror
2. Understand the parameter in realtime interferometer control in order to reconstruct the gravitational wave signal.

Where is Photon Calibrator in KAGRA?




Receiver module
Periscope
Transmitter module
cal. beam
main beam
cal. beam
Displacement
Image picture
Telephoto camera
36m

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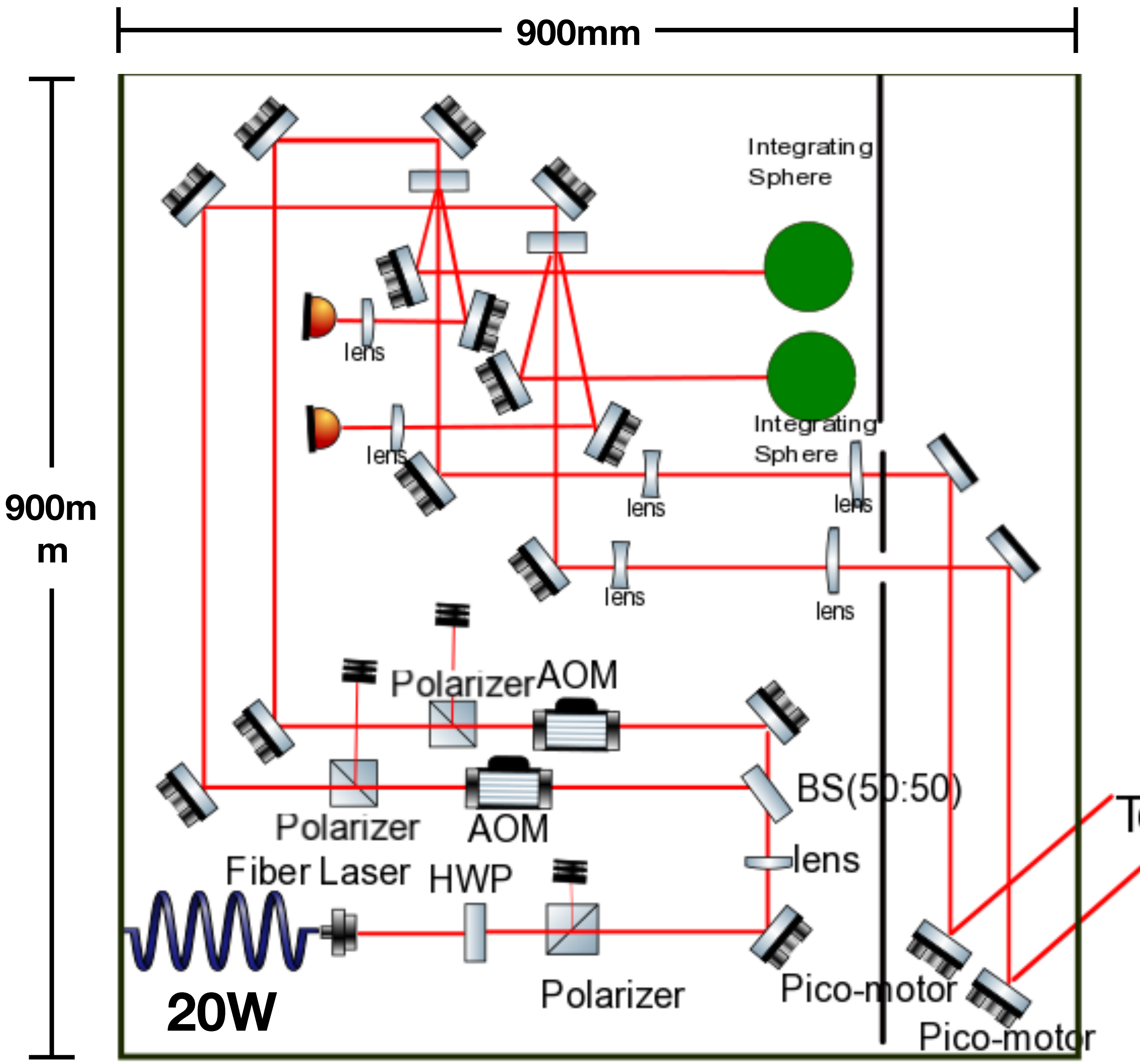
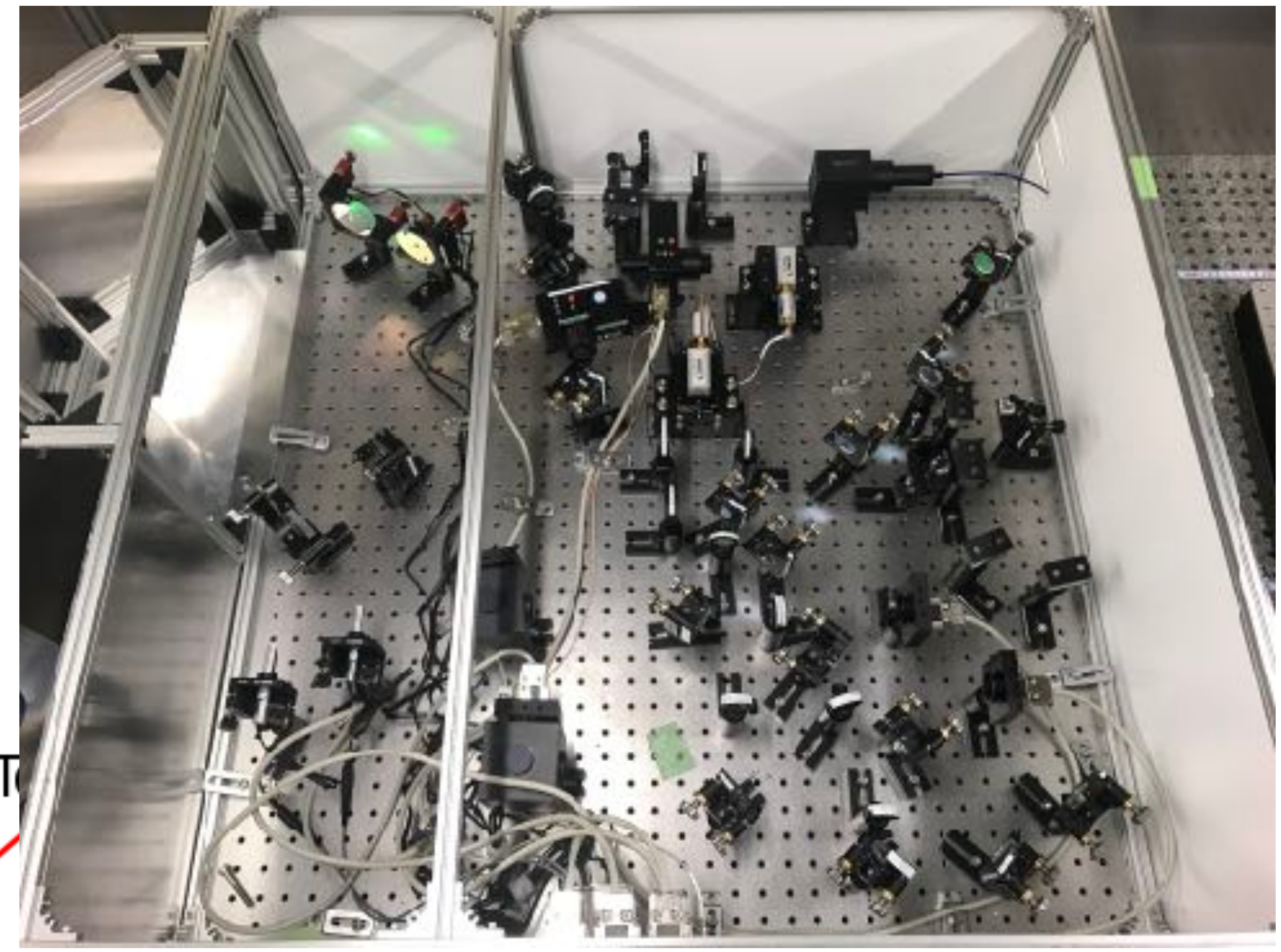
Transmitter Module

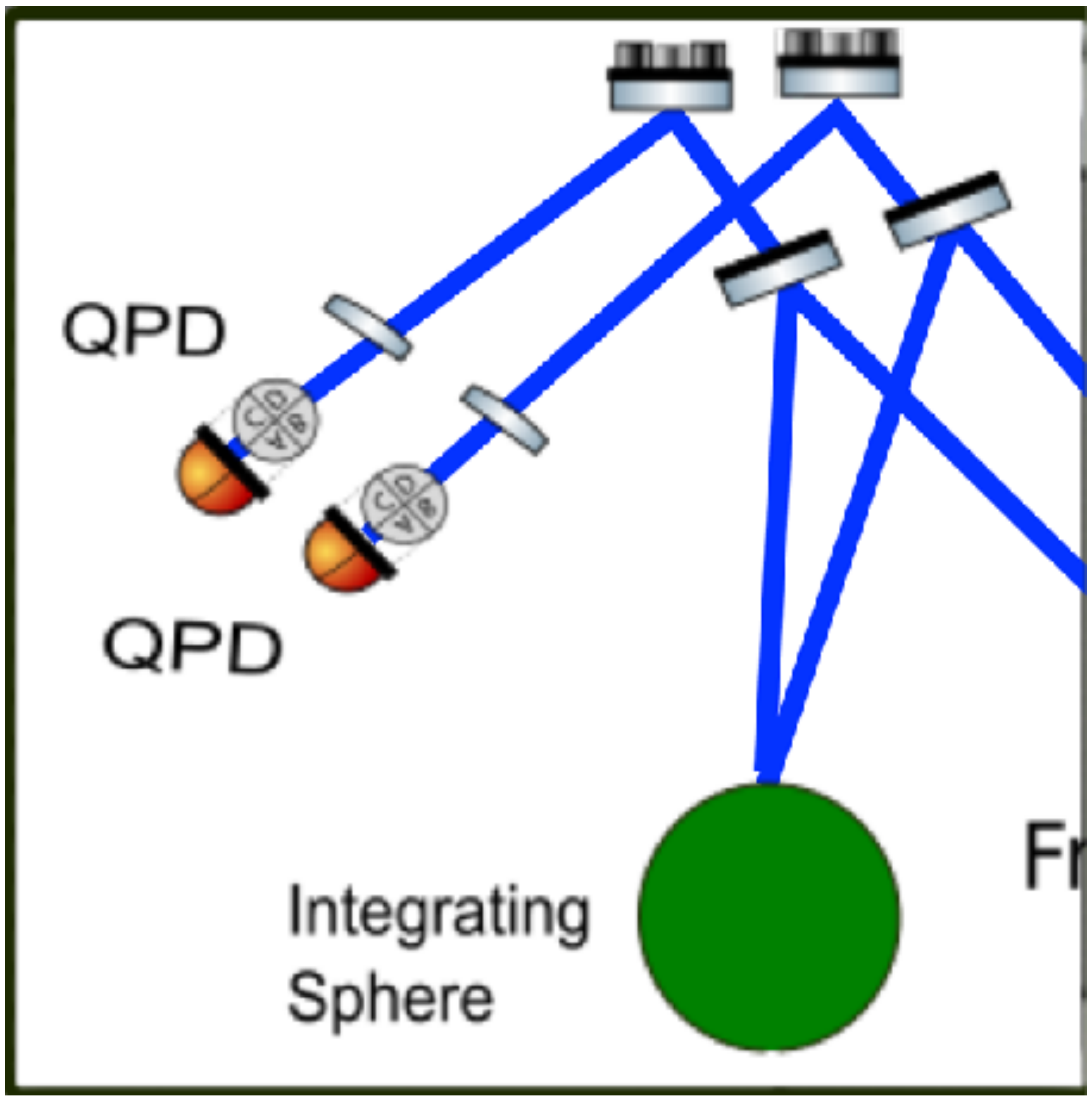




2 innovations compared to LIGO:

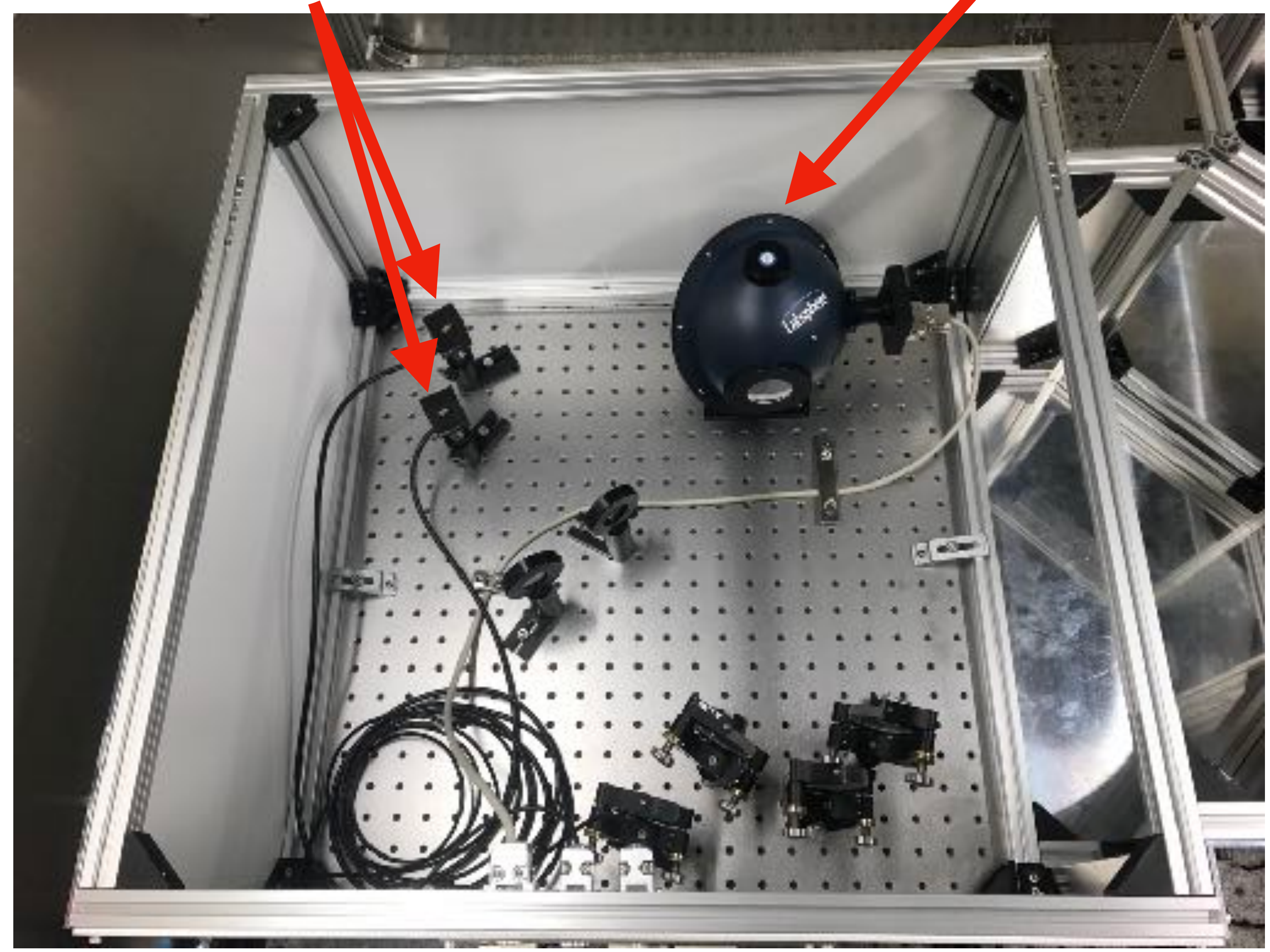
1. **20 watts high power laser**
2. **2 Acoustic Optic Modulator (AOM)**

Receiver Module



QPD
Quadrant Photo Diode: Monitoring the beam position

RxPD
Integrating sphere at Rx



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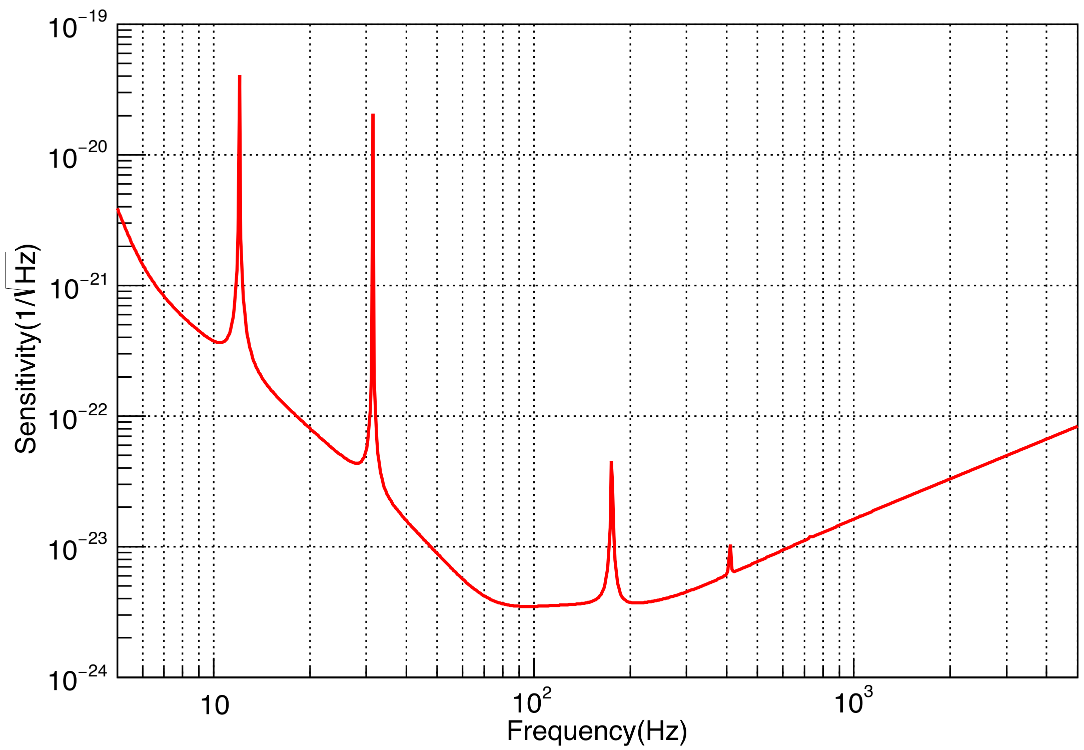
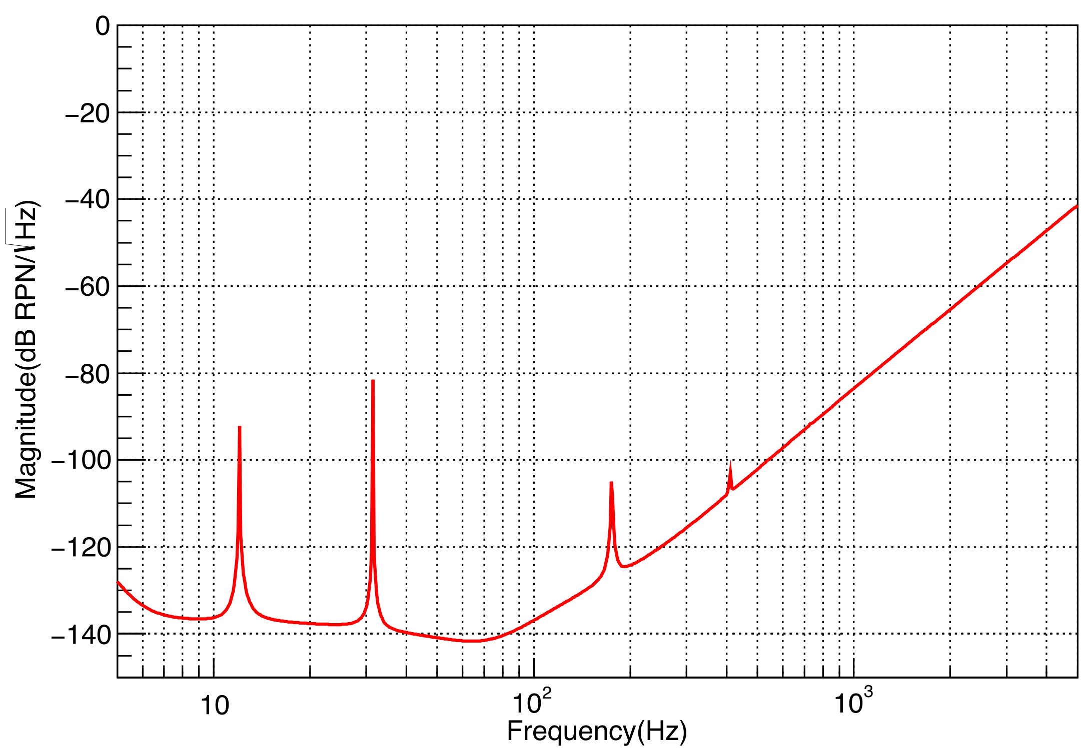
Relative Power Noise Requirements

KAGRA strain sensitivity



Pcal requirement



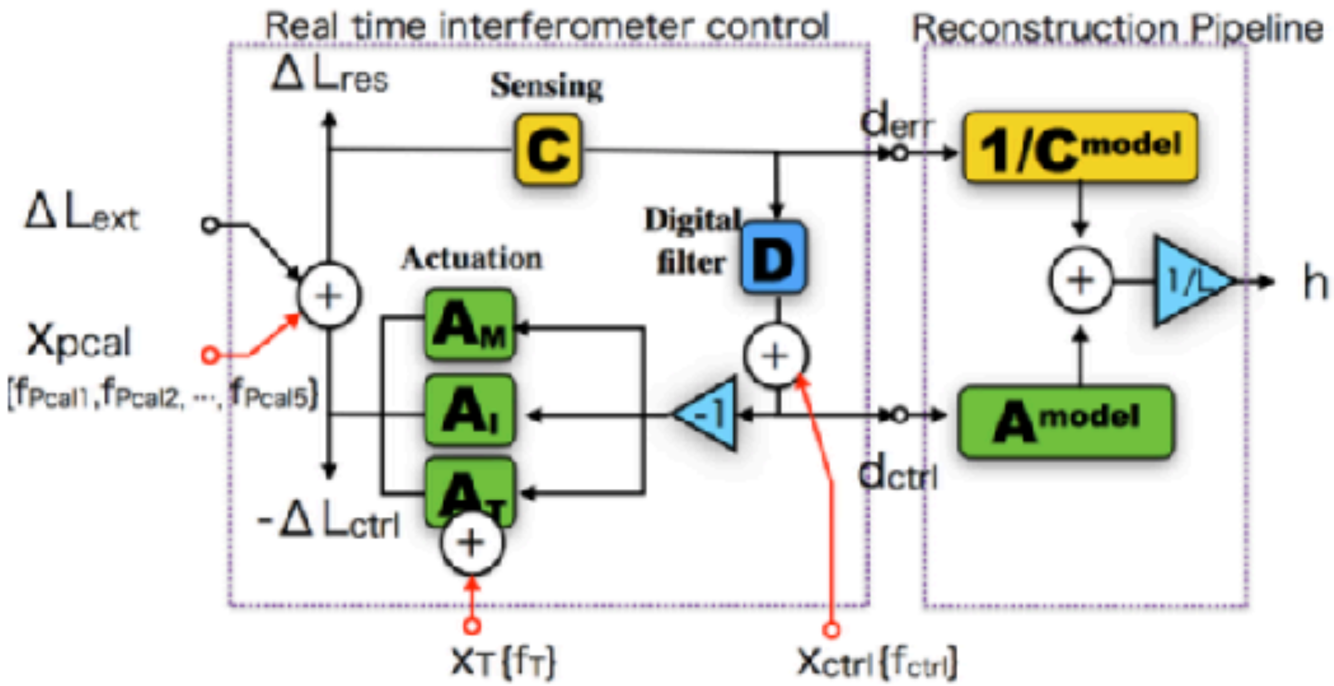
$$\Delta L(f) = \underbrace{\frac{2\Delta P\cos(\theta)}{c}}_{\text{Force}} \underbrace{\frac{1}{M(2\pi f)^2}}_{\text{Force to length transfer function}} < \frac{1}{10}\Delta h(f) L$$

strain sensitivity curve of KAGRA (→ $\Delta h(f)$)

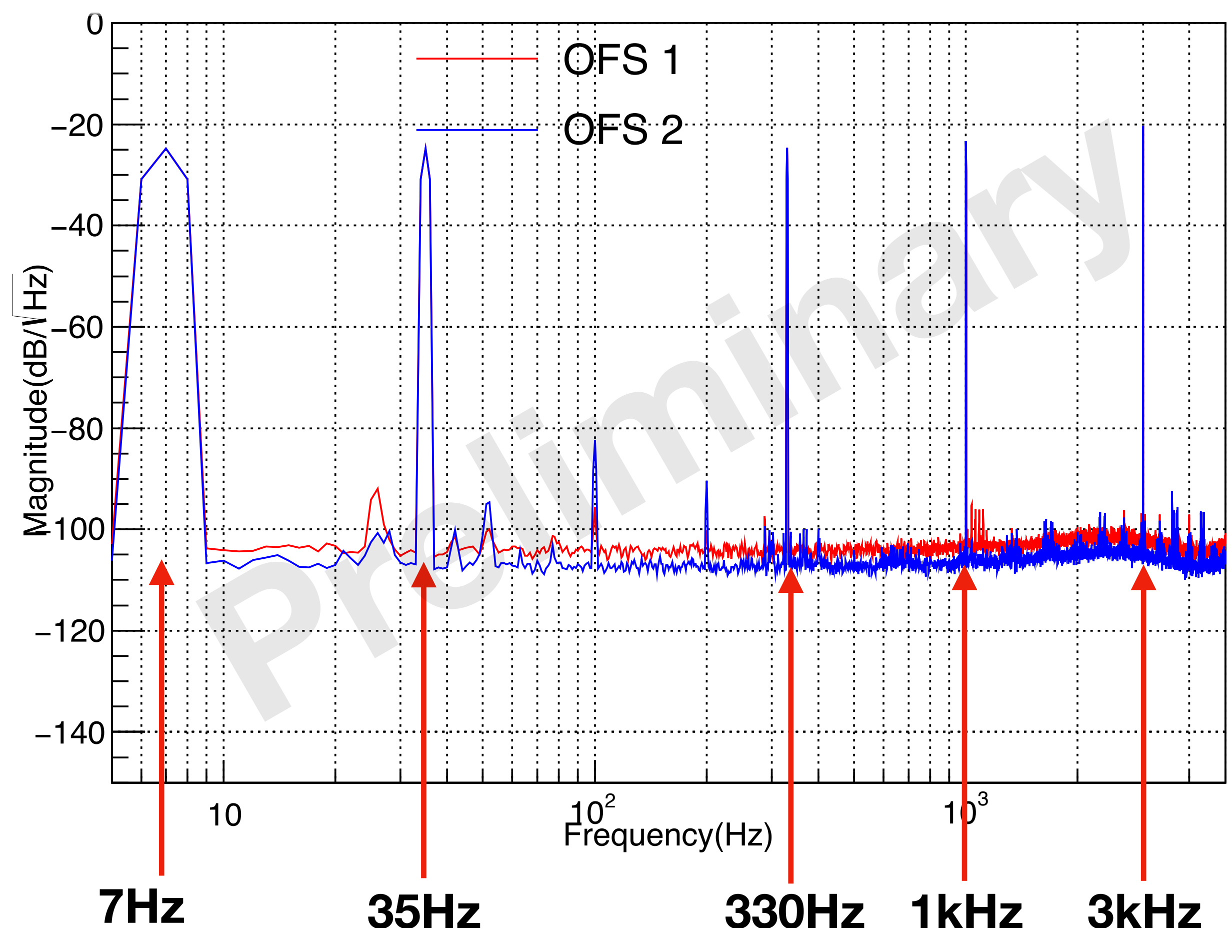
$$RPN = \frac{\Delta P}{P} = \frac{Mc(2\pi f)^2 \Delta h(f) L}{20P\cos(\theta)}$$

M: ETM Mass (23kg)
c: Speed of light
L: Arm length of Interferometer (3km)
P: Laser Power (10W)

Calibration Lines

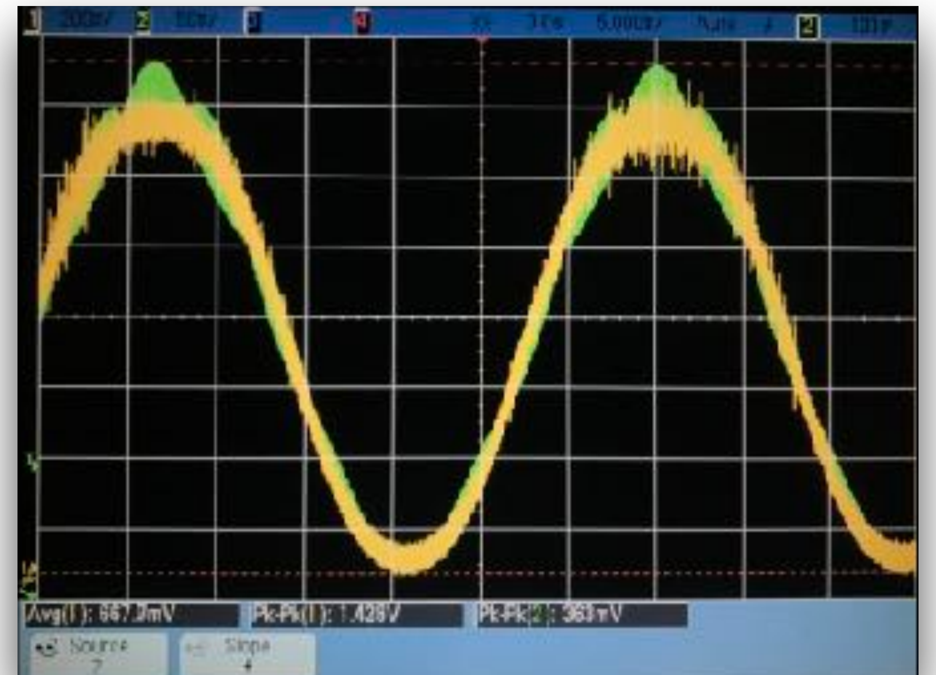


Line name	Cal.	Frequenc
Xpcal	f_{pcal1}	~7Hz
	f_{pcal2}	35Hz
	f_{pcal3}	~330Hz
	f_{pcal4}	~1000Hz
	f_{pcal5}	~3000Hz
Xctrl	f_{ctrl}	~35Hz
XT	f_T	~35Hz



Harmonic Noise Requirements

35Hz modulation



FFT

35Hz 70Hz 105Hz 140Hz

After defining the requirement of relative power noise, we need to decrease the peaks of higher harmonic noise to below the requirement curve.

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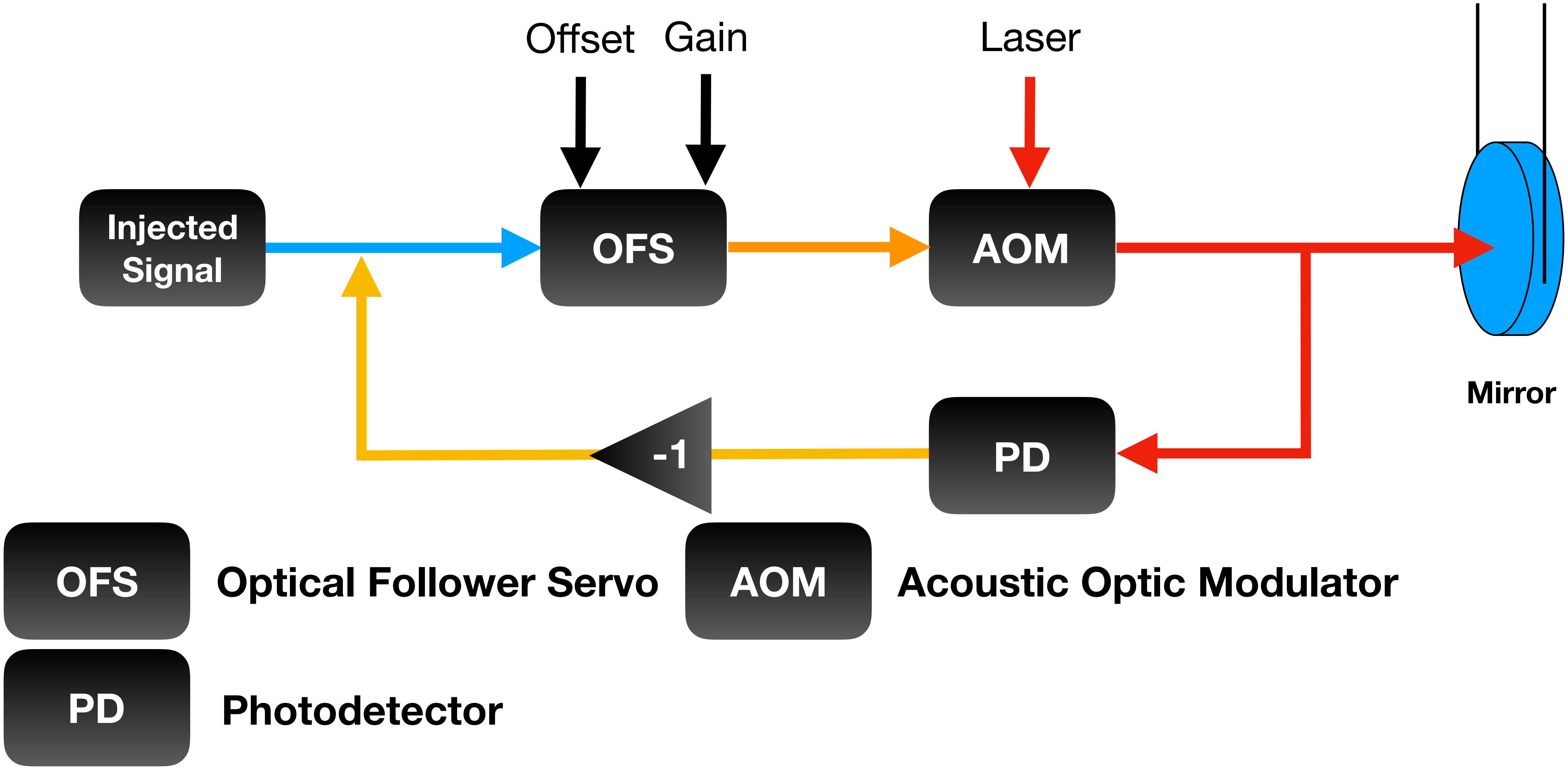
Power stabilization



We use Optical Follower Servo and photodetector to make a closed-loop in order to reduce the noise of laser.

Optical Follower Servo

OFS Back Board
Ver. 1

OFS Front Board
Ver. 4

OFS & Interface Chassis

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Measurement Plan

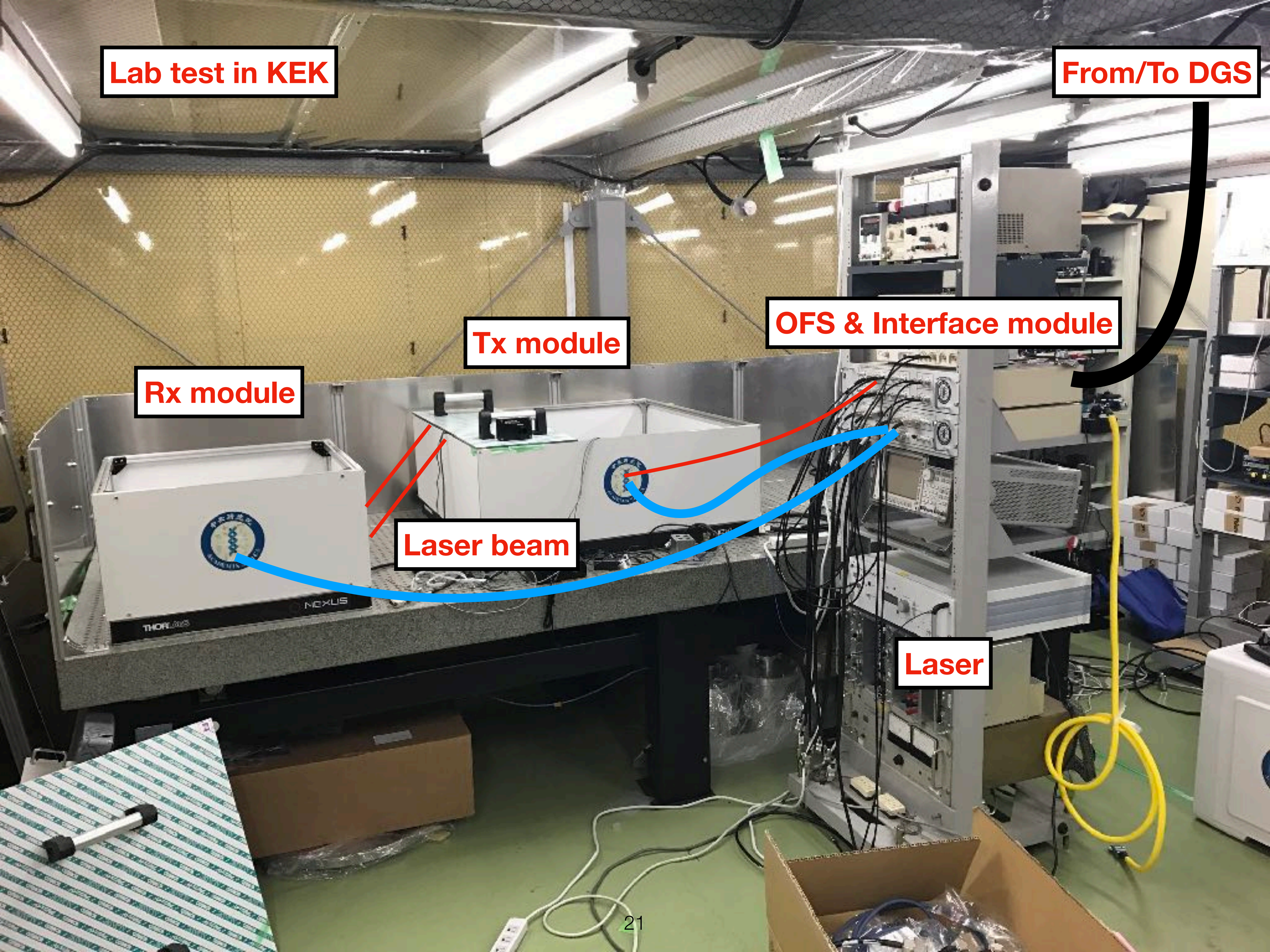
Lab test: KEK

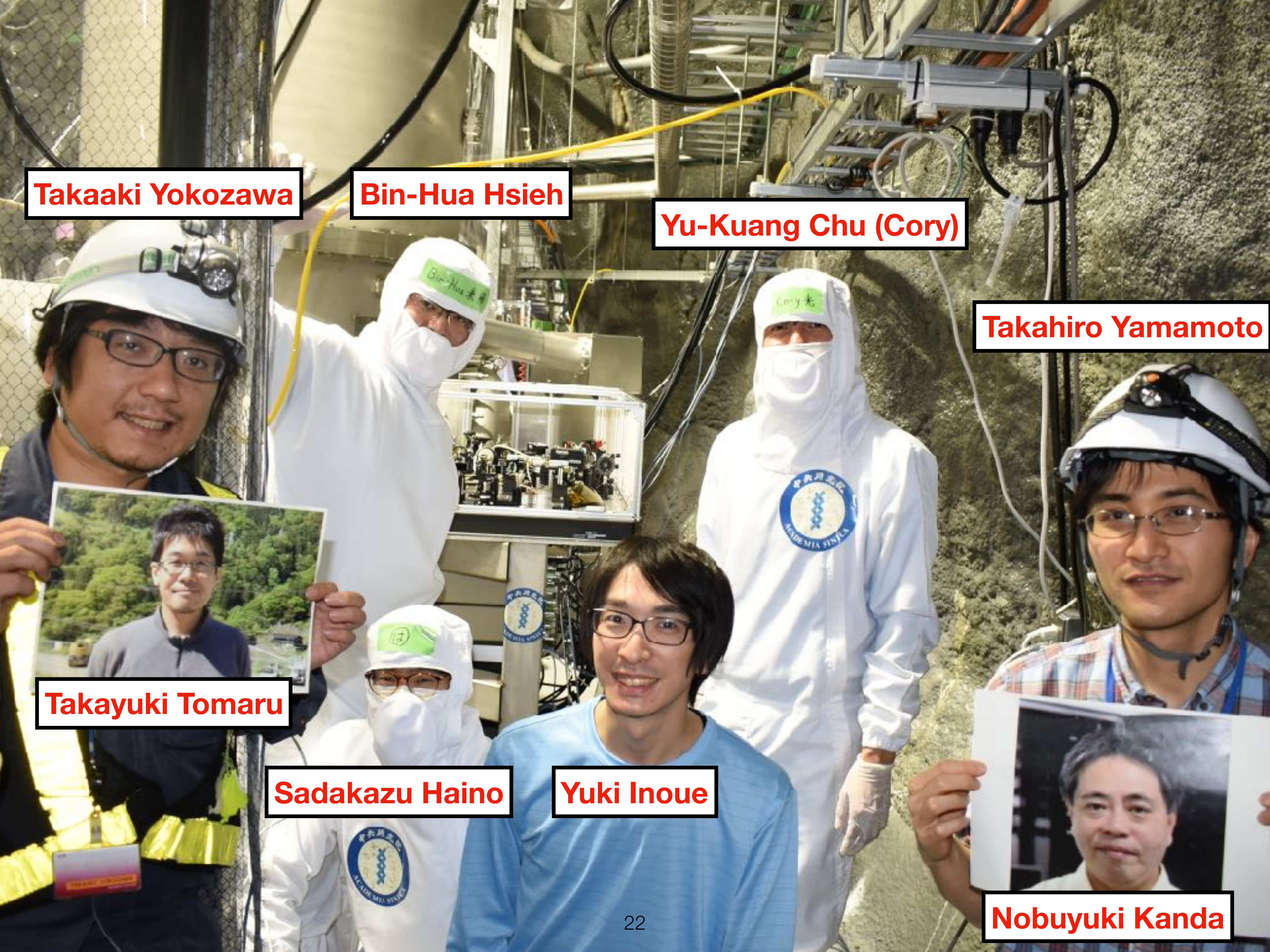
- **Develop Photon Calibrator** ✓
- **Measurement:** ✓
    1. **Transfer function** ✓
    2. **Relative Power Noise** ✓
    3. **Higher Harmonic Noise** ✓
    4. **Peak stability** ✓

Analysis is still ongoing

Kamioka test: KAGRA site

- **Assemble Photon Calibrator** We are here!
- Measurement:
    1. Transfer function
    2. Relative Power Noise
    3. Higher Harmonic Noise
    4. Peak stability


Lab test in KEK
From/To DGS
OFS & Interface module
Tx module
Rx module
Laser beam
Laser
NEXUS
THORLABS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Takahiro Yamamoto
Takayuki Tomaru
Sadakazu Haino
Yuki Inoue
Nobuyuki Kanda

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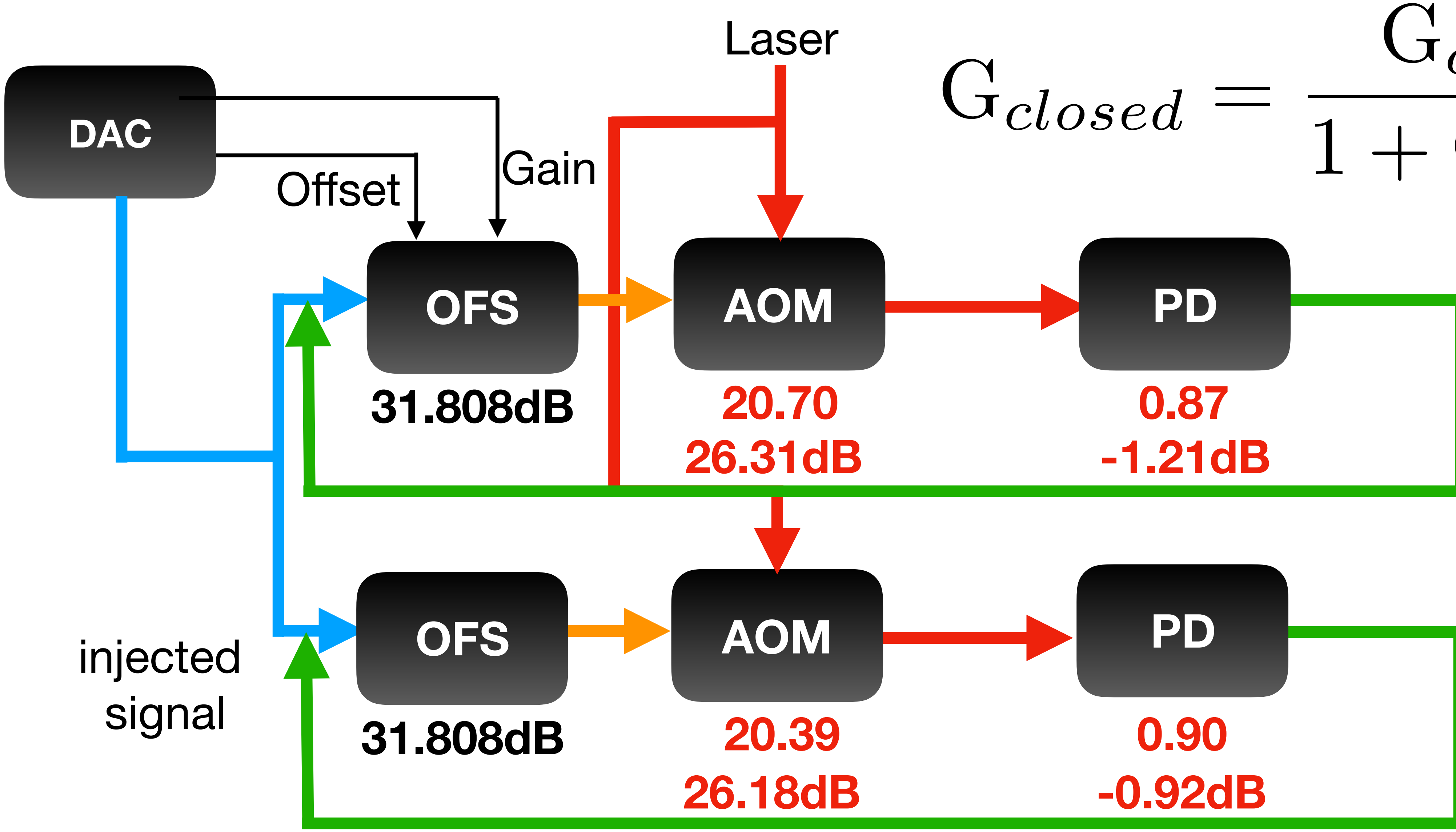
Transfer function



$$G_{closed} = \frac{G_{open}}{1 + G_{open}}$$

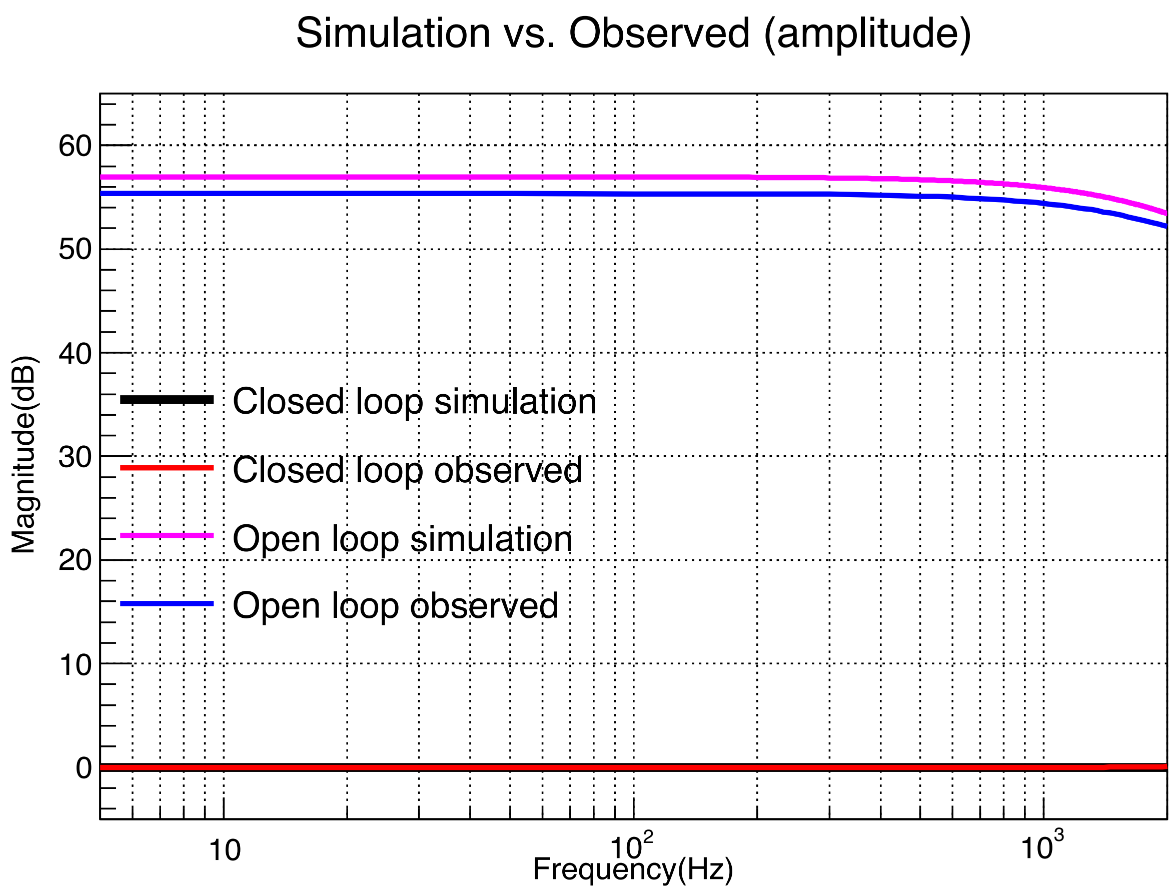
Open-loop Gain

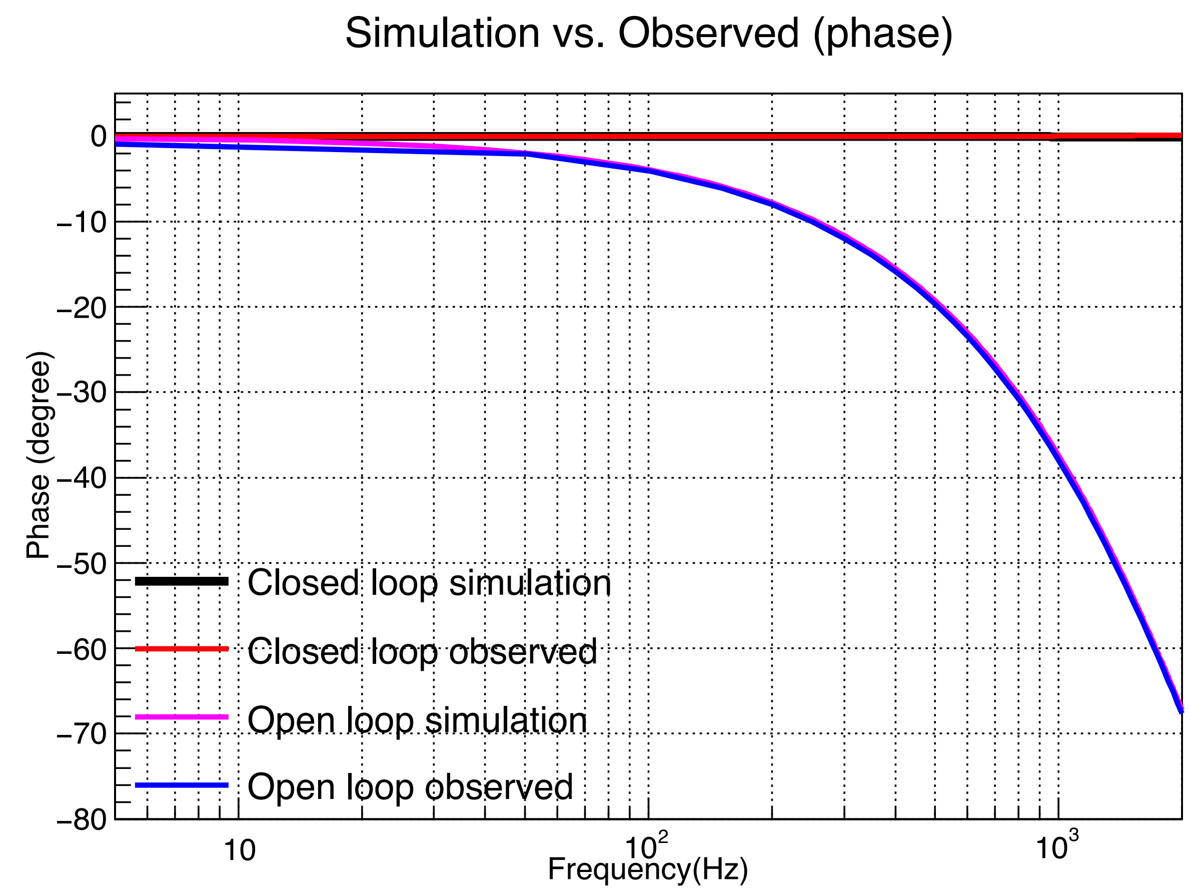
OFS1:56.91dB
OFS2:56.07dB

Closed-loop Gain

OFS1:-0.0124dB
OFS2:-0.0136dB

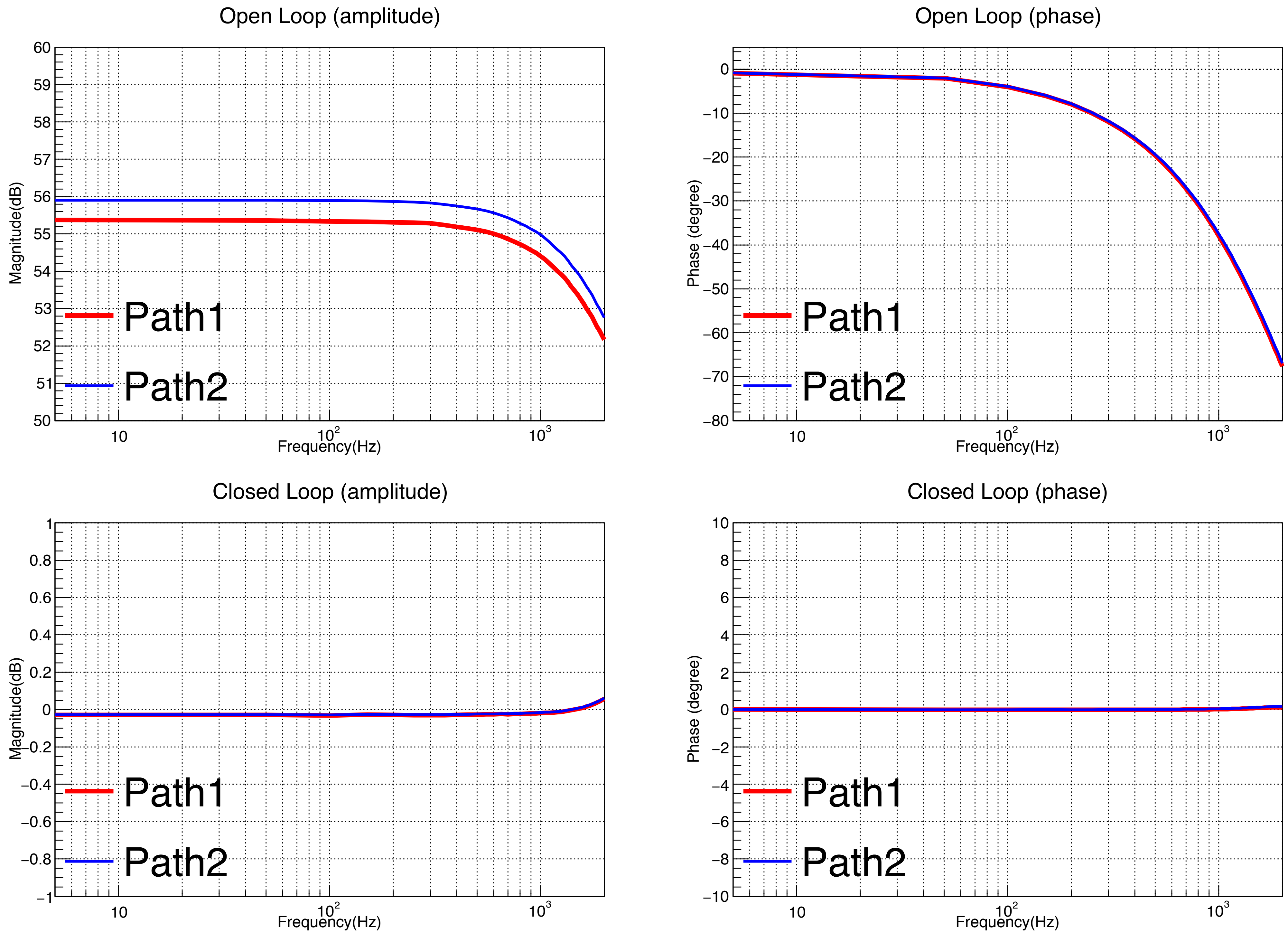
Transfer function





$$G_{closed} = \frac{G_{open}}{1 + G_{open}}$$

Observed results consist with simulation result.



$$G_{closed} = \frac{G_{open}}{1 + G_{open}}$$

Path 1 result is consistent with Path2 result.

Summary

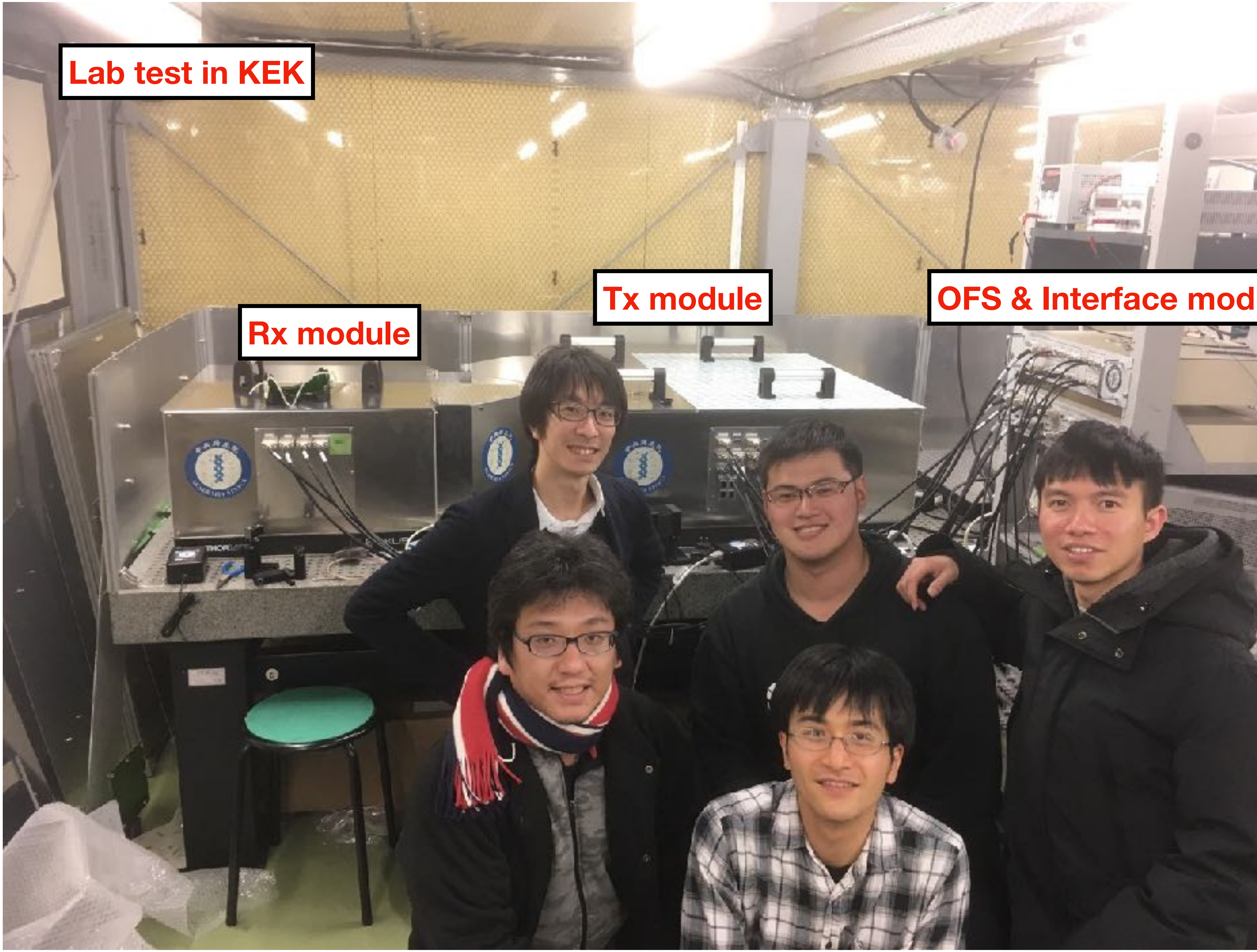
- We built a Photon Calibrator with 20W laser for the reconstruction of gravitational wave.
- We used Optical Follower Servo to make a closed-loop feedback control in order to decrease the noise of laser power.
- We finished the lab test in KEK, and we are going to move on to KAGRA site test.
- The measurement results of transfer function consist with simulation results, and each paths also consists with each other.

Future Plan

- We are assembling Photon Calibrator and will characterize it in KAGRA site.
- We will measure the
  - transfer function,
  - relative power noise,
  - higher harmonic noise
  - peak stability

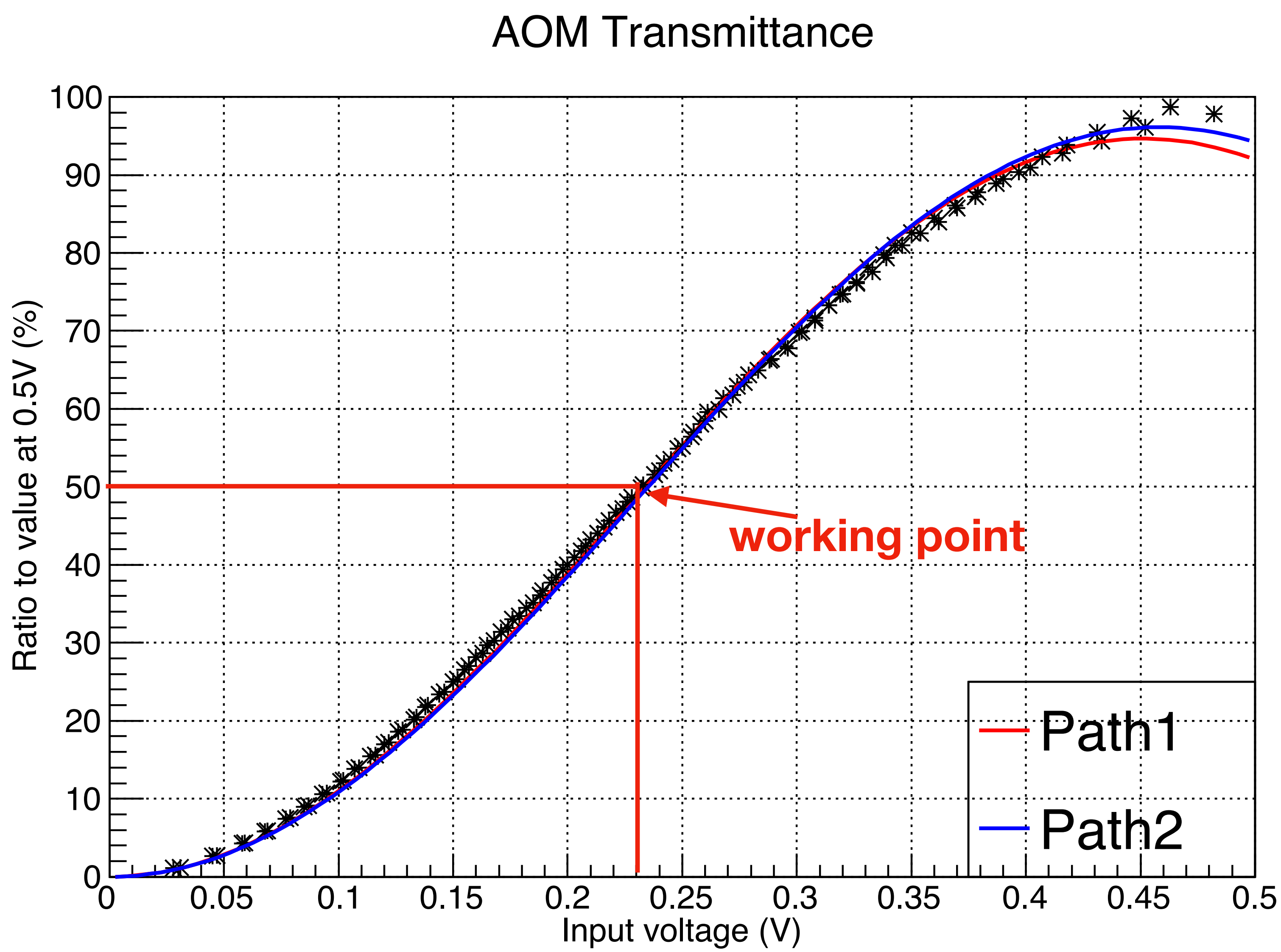
  in KAGRA site, and compare the result with lab test.

Supplementary


Lab test in KEK
Rx module
Tx module
OFS & Interface module

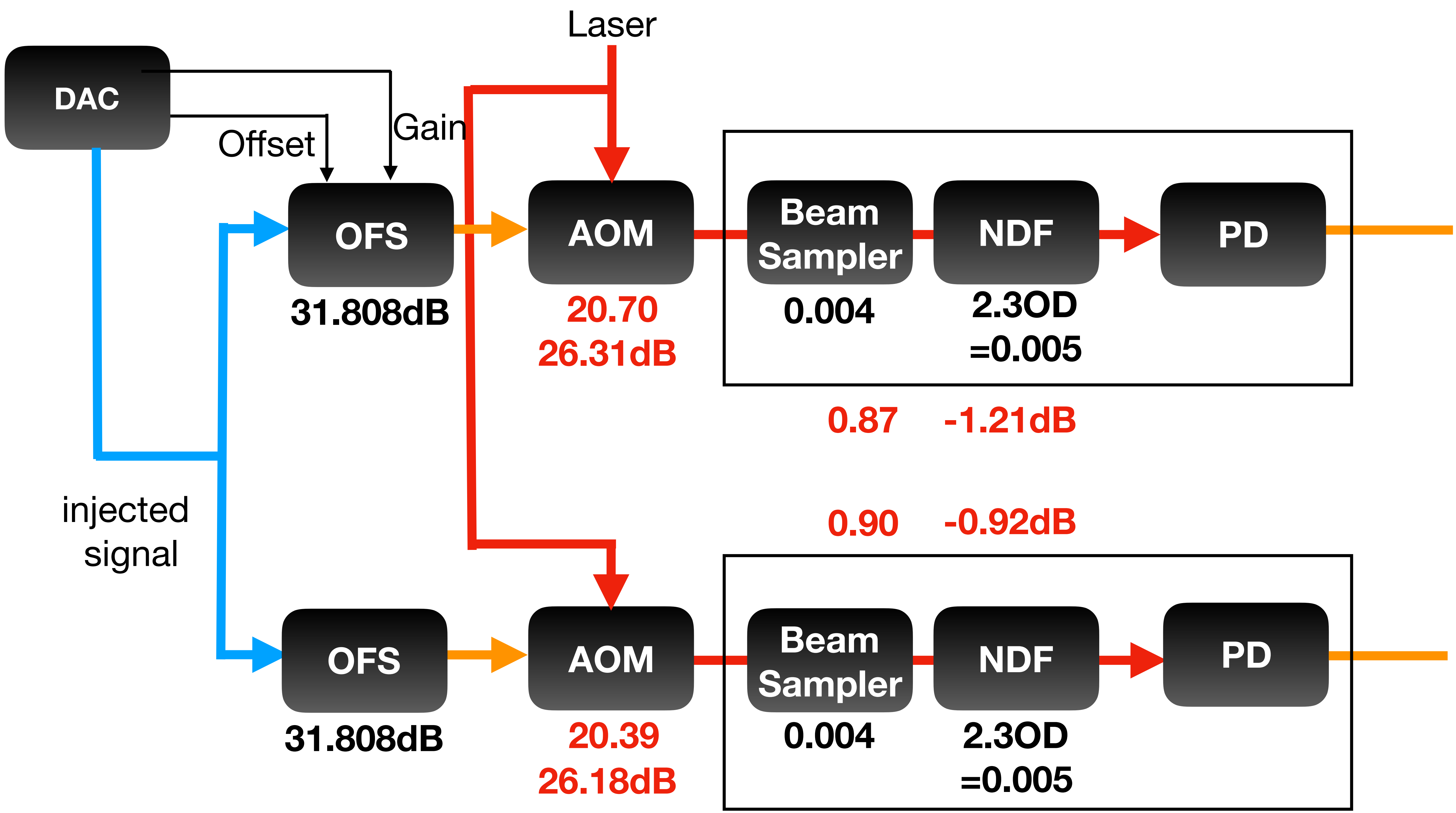
AOM transmittance

AOM transmittance divided by the peak value at 0.5V input



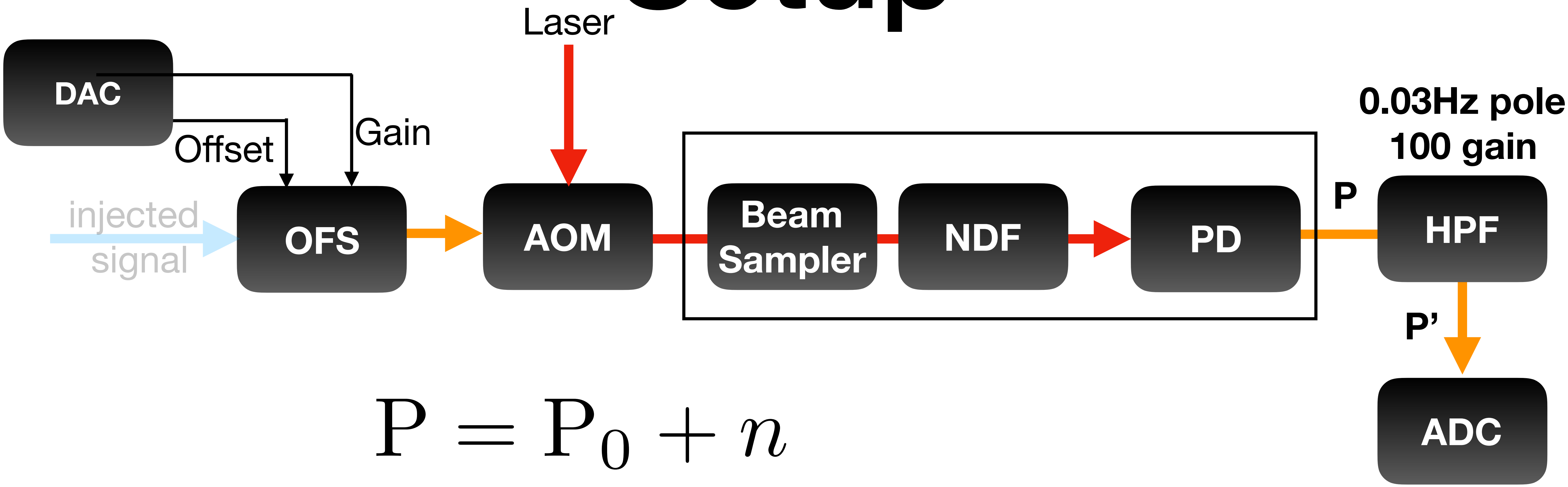
working point: input voltage at 0.23V

Transfer function



Open-loop TF **OFS1:56.91dB**
OFS2:56.07dB

Setup



$$P = P_0 + n$$

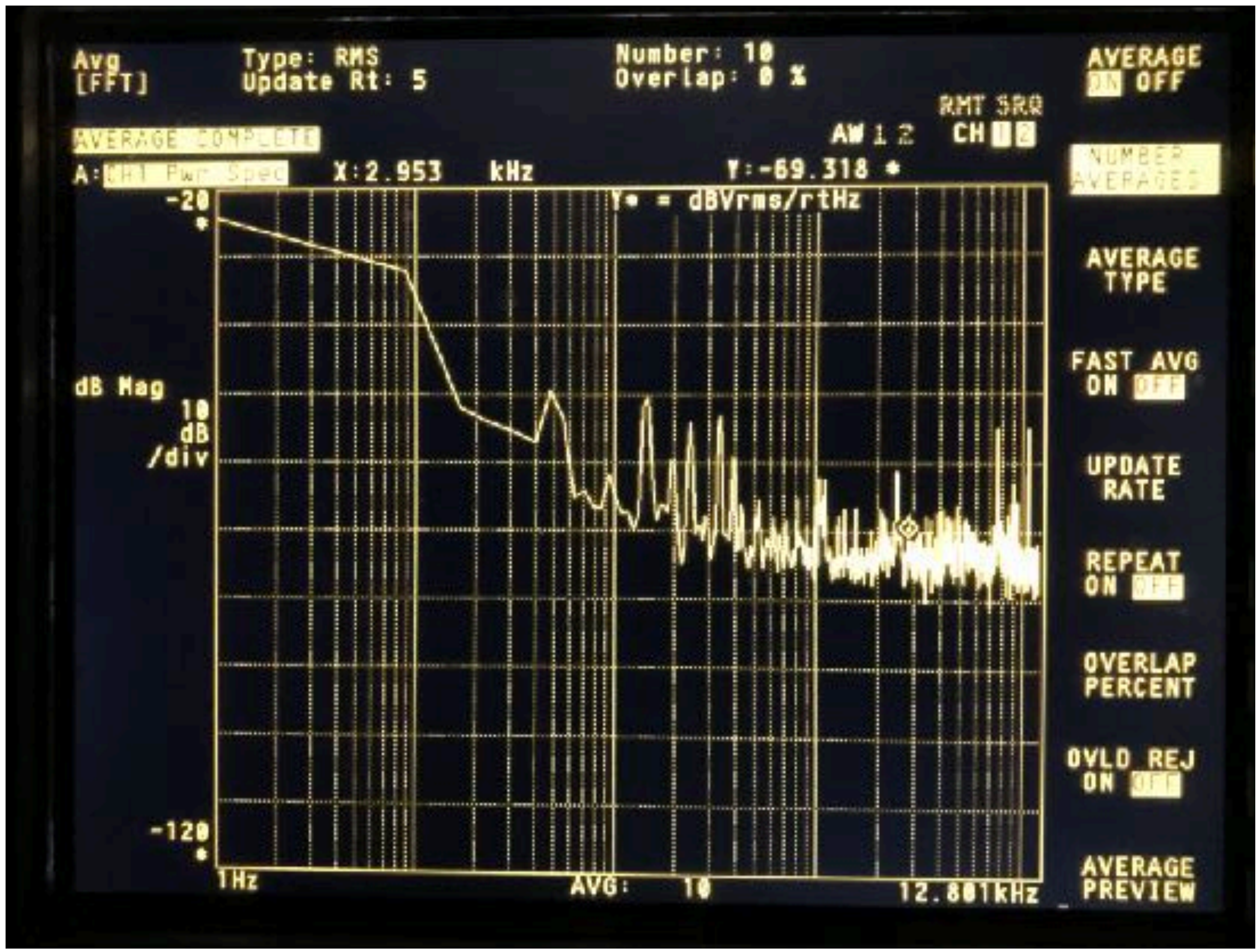
$$P' = P'_0 + n' \approx gn(P'_0 \approx 0)$$

$$\mathrm{RPN} = \frac{n}{P_0} = \frac{n'}{gP_0}$$

In our measurement, P_0 comes after PD. Therefore, $g = 100$

DAC noise

- I use spectrum analyzer and g=1000 (60dB) amplifier to check the noise level of DAC.



The noise level of DAC is -130Vrms/rtHz. In our measurement which DC signal of PD is around 3V, this DAC noise is around -140dB/rtHz.

Noise floor by changing Offset and Gain (Open loop)

- I measured closed loop noise level and open loop noise level of OFSPD1 with different gain and offset using spectrum analyzer.

Noise floor by changing Offset and Gain (Open loop)

To AOM(V)	Gain (dB)	OFS1 Offset	OFS2 Offset	OFS1 RPN	OFS2 RPN
0.1	0	0.12	0.12	-108.73	-108.73
	15.174	0.042	0.04	-97.73	-97.73
	31.808	0.0288	0.0277	-77.73	-77.73
0.2	0	0.22	0.22	-112.6	-112.96
	31.808	0.0314	0.0302	-87.6	-87.95
0.225	0	0.246	0.246	-114.13	-114.43
	31.808	0.032	0.0308	-89.13	-89.43
0.3	0	0.325	0.32	-115.67	-115.67
	31.808	0.0342	0.033	-92.67	-92.67
0.4	0	0.43	0.424	-114.82	-115.22
	31.808	0.037	0.0356	-99.82	-100.22

Noise floor by changing Offset and Gain (Closed loop)

To AOM(V)	Gain (dB)	OFS1 Offset	OFS2 Offset	OFS1 RPN	OFS2 RPN
0.1	31.808	0.8	0.8	-127.73	-127.73
0.2	31.808	2.5	2.6	-124.60	-124.96
0.225	31.808	3	3.1	-124.40	-124.71
0.3	31.808	4.3	4.5	-122.61	-122.87
0.4	31.808	5.5	5.8	-127.74	-125.19

Discussion

1. From closed Loop measurement, change the offset doesn’t effect the noise level too much.

2. From open loop measurement, we can see that if the gain increases, the noise also increases. If we decrease the gain in close loop measurement, then the noise level might decrease. Then we need to sacrifice the high gain in close loop feedback control.