Towards the advanced modulation system using the Mach-Zehnder interferometer for the detuned RSE

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1. Abstract

For KAGRA, in which the quantum noise limits the sensitivity in a broad frequency band because of its cryogenic system, the detuned RSE (DRSE) is the most powerful mode of the interferometer. We plan to use a Mach-Zehnder interferometer (MZI) with a delay line, Fig. 1, as the modulation system for the length sensing of main interferometer. This enables to relax the noise requirement, especially the photo detector noise (PDN) and the oscillator phase noise (OPN) [2]. Moreover, by generating the f3 sideband, which is pure AM, the control of the main interferometer can be more robust than the third harmonics demodulation (THD) in the lock acquisition phase.

On the other hand, we need to consider the noise in MZI itself. Here, we explain how the modulation system works and report the requirement on the displacement noise of mirrors we derived, which seems feasible, and the test of PZTs, which shows good result.

2. Modulation System ~MZI with Delay-Line~

The MZI generates three sidebands, f1, f2 and f3. The fixed length of delay line is determined so that the f3 sideband become pure AM, i.e. θ in formula below becomes π. θ of the other sidebands is accordingly set.

$$E_{out} = E_{in}e^{i\Omega t}\{1 + \left|4\sqrt{2}m\sin\left(\frac{\varphi}{2}\right)\sin\left(\frac{\theta}{2}\right)\right|\cos\left(\omega_m t + \frac{\theta+\varphi-\pi}{2}\right) + i\left|4\sqrt{2}m\cos\left(\frac{\varphi}{2}\right)\cos\left(\frac{\theta}{2}\right)\right|\cos\left(\omega_m t + \frac{\theta+\varphi-\pi}{2}\right)\} \quad (1)$$

E_{in} : incident laser
E_{out} : f1 or f3 sideband after MZI with ideal fringe
θ : phase difference by delay line
φ : phase difference by shifter b/w EOMs
m : modulation index

➢ How the modulation system works (Fig. 2)

By changing the phase difference b/w the EOMs, φ, we can easily switch from the BRSE to the DRSE and vice versa.

➢ The strong point of the f3 AM sideband (Fig. 3)

In principle, we can completely remove the signal couplings b/w the arm and center region of the main interferometer.

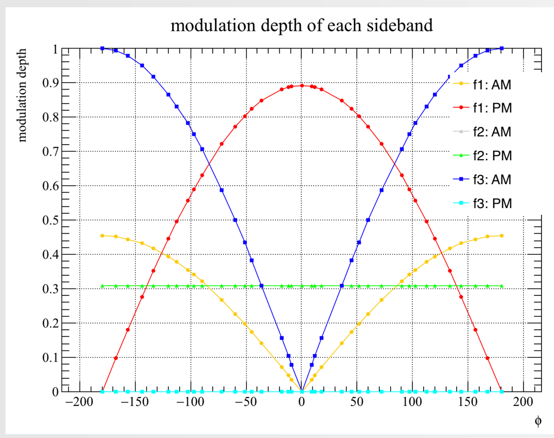

Fig. 2 φ vs Modulation index

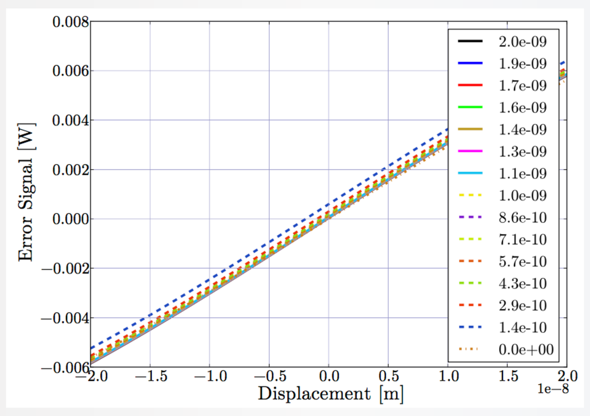

Fig. 3 THD MICH error signal with various CARM offset from reference [1]

	frequency [MHz]	modulation type	Signal extraction
f1	16.88	PM & AM	MICH & SRCL
f2	45.02	PM	PRCL
f3	56.27	AM	Local oscillator for center

Table 1. sidebands by MZI

3. How to relax the requirement on DRSE

The noise requirements are basically more strict for the DRSE than that for the BRSE. Based on reference [2], we show how the f1 AM works for relaxing them and enables us to realize the DRSE more easily. The basic idea is to cancel out the AM component produced by detuning the SRM with the f1 AM sideband generated beforehand.

Out of various excess noises caused by the detuning, the two below are the most disturbing.

PDN : Once the power on a PD gets higher, PD may be saturated. In such a case, we need to reduce gain of the PD, which leads the reduction of resolution of the PD. With the f1 AM, we can improve the PDN at the signal port of SRCL.

OPN : For the Q-phase signal, with the detuned RSE, OPN has the AM component, which can be ultimately the noise of the detector.

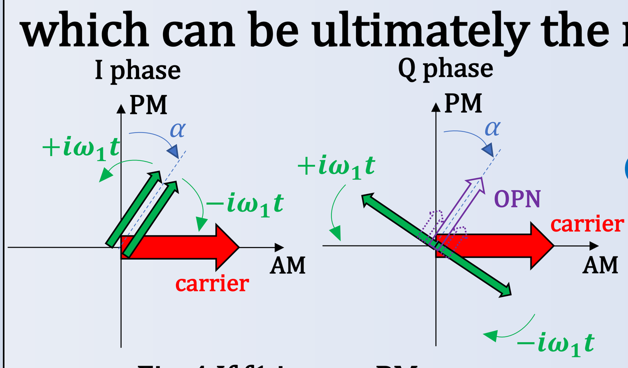

Fig. 4 If f1 is pure PM
Left: PDN, *Right*: OPN

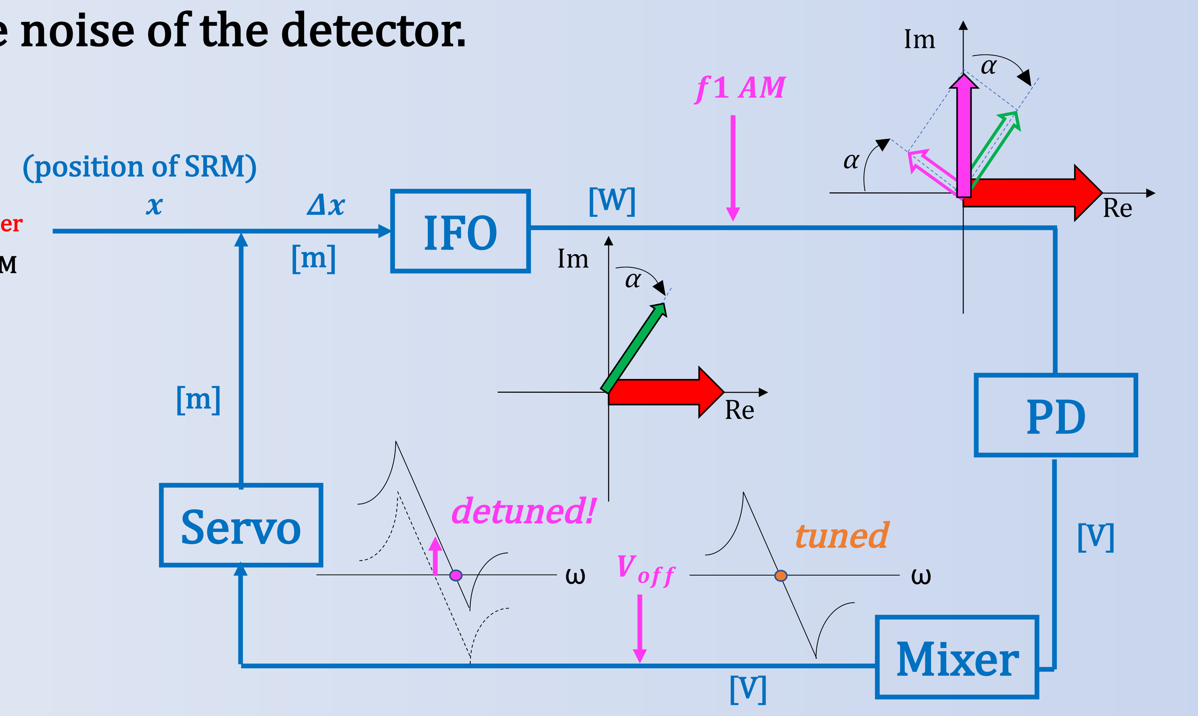

Fig. 5 Block Diagram of SRCL Loop

from laser source

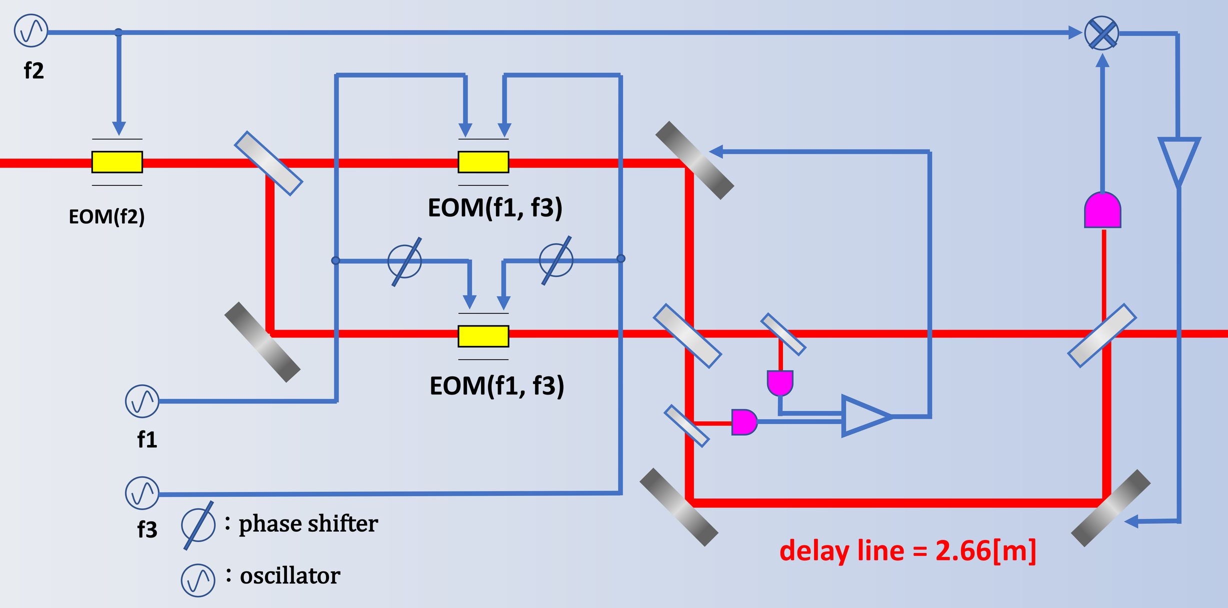

Fig.1 configuration of the modulation system

to main interferometer

4. Simulation

We show the result of the simulation, i.e.

➢ Requirement on the displacement noise of the MZI
➢ Assumed shot and seismic noise
-> feasibility of the modulation system

The mirror displacement noise in the MZI causes various types of noises on the output of the MZI, see lower right panel in Fig. 6. The requirements should be set by the greatest noise in each frequency region. In terms of seismic noise, the UGF of 10kHz is needed to suppress it under the condition below.

The variety of laser noise caused by MZI

frequency × modulation type × noise type
(f1, f2) (AM, PM) (Amplitude, Phase)

simulation condition

➢ Laser Power
incident : 180[W]
pick off for mid-fringe : 10[mW]
➢ Control Loop
Linear low-pass filter
pole = 1.0 [Hz]
UGF = 10kHz - (A)
➢ MZI
no generation of f1 AM - (B)

*Notice
(A) unreachable with digital control
(B) on the mid fringe, the requirement is expectedly relaxed by two digits

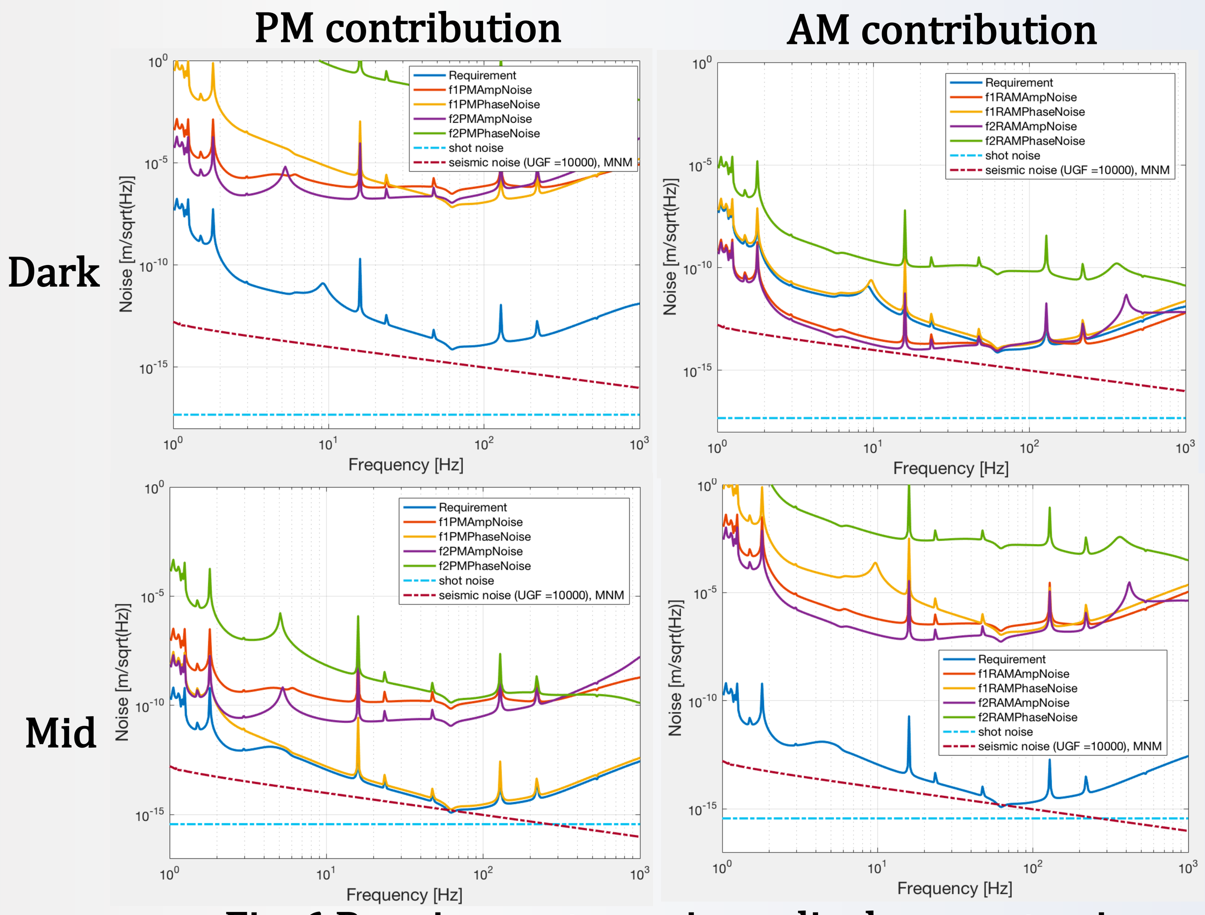

Fig. 6 Requirement on mirror displacement noise

5. Experiment –Test of PZT-

As a preliminary experiment, we evaluated the performances of PZT and mirror with a simple MZI, as shown in Fig.7. Here we show

➢ The UGF of 15.6kHz with the PZT, which is over 10kHz
<- the usage of a light PZT & half-inch mirror
➢ Good current sensitivity
->almost meet the requirement

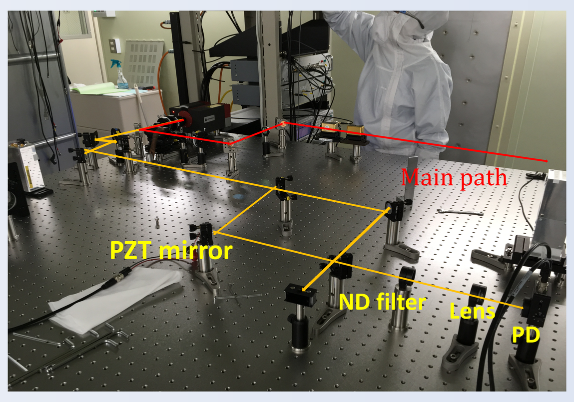

Fig.7 Laser picked off

experiment condition

➢ Filter : SR560
DC gain = 2e4
pole = 10 [Hz]
➢ Optical component
PZT : PA44LEW (thorlabs)
*PZT mirror : HYD-05 (AUTEX)
➢ Laser Power on PD
~ 1.8 [mW]
*Half-inch mirror

Fig.9 shows the sensitivity curve in this setup. Following reasons can be assumed why the measurement didn't totally reach requirement.

➢ Laser Power is low (~1.8 [mW])
➢ Asymmetry of paths -> low quality of resonance half-inch mirror for PZT
➢ usage of SR560, which accept at most 2[V]
➢ no usage of differential readout

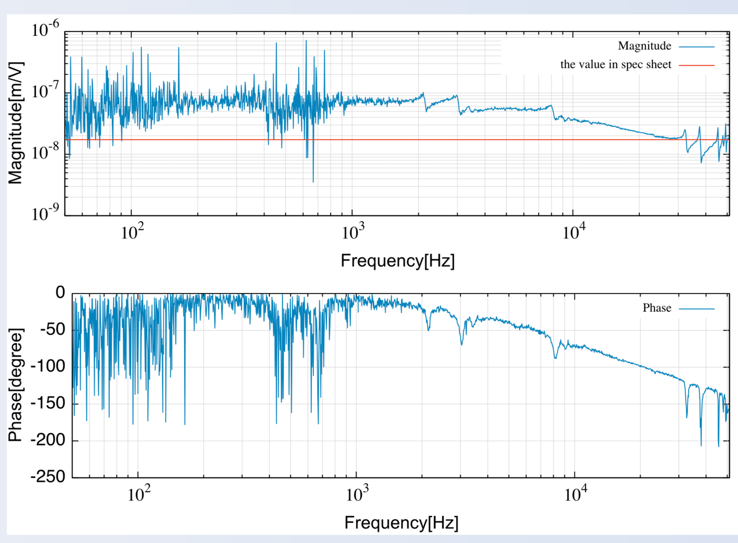

Fig. 8 PZT Efficiency

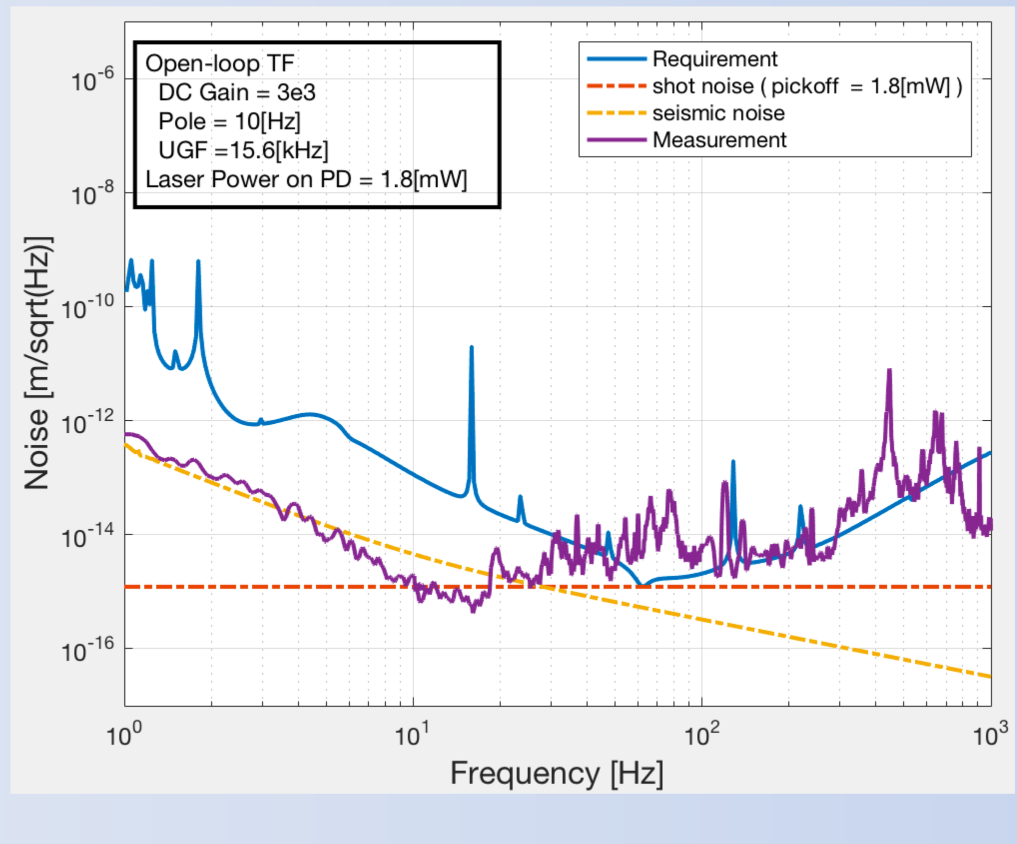

Fig. 9 Current sensitivity of the mid-fringe MZI

6. Future Plans

➢ May – August, 2018 :
- determine the most proper optical component through careful measurements
- configure the full MZI in the main path and check if we can control it well

➢ For bKAGRA Phase 3
- test of MZI with amplitude difference b/w EOMs, which is necessary for cancelling out AM components in Q-phase
- commissioning work with the detuned RSE

References

[1] KAGRA Main Interferometer Design Document
[2] S.Ueda et al., Class. Quantum Grav. 31 (2014) 095003