Design and experimental demonstration of Mach-Zehnder modulation system

The authors of MZM paper:

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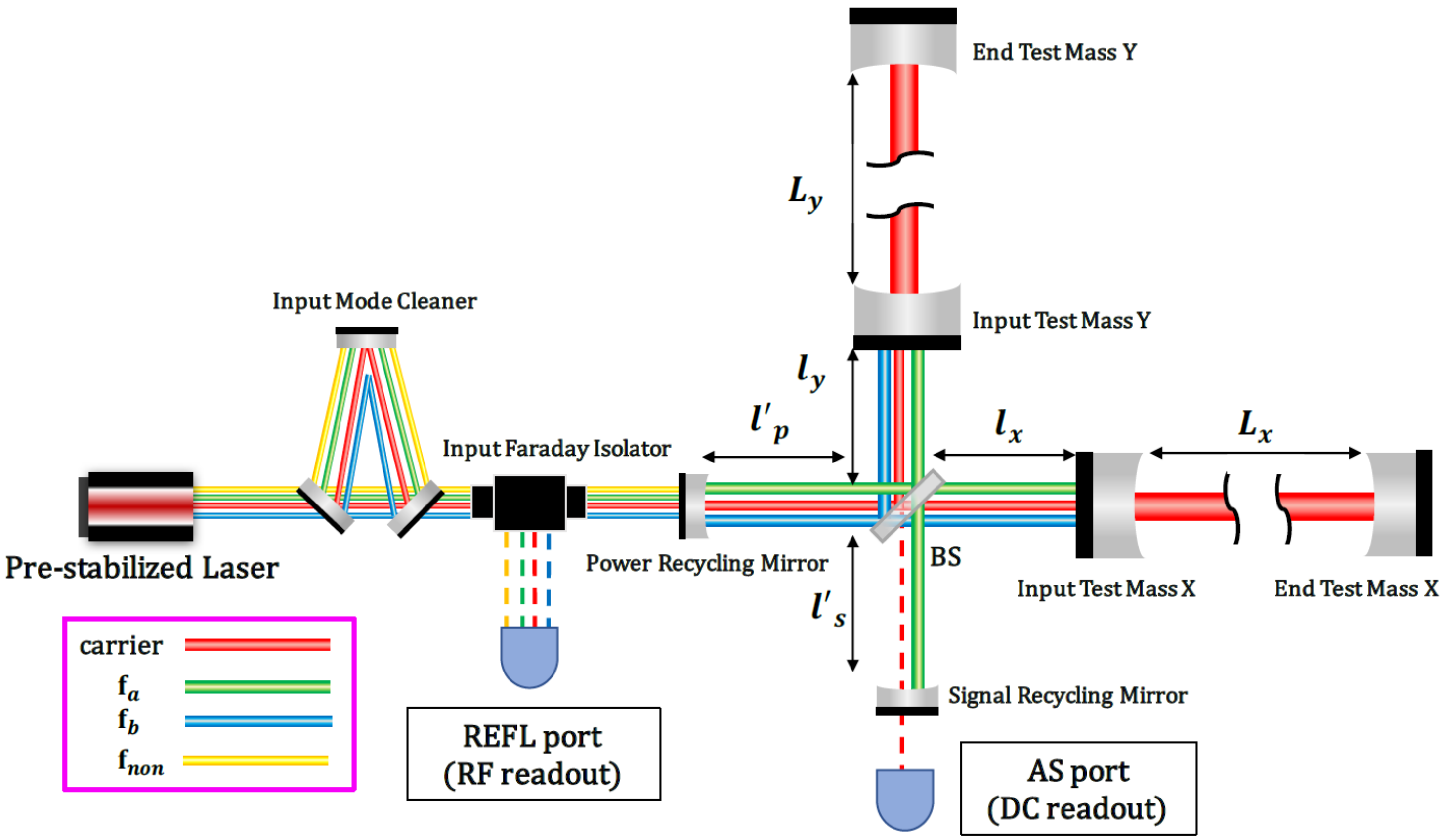
- Why use MZM
- Displacement noise requirement
- Experiment
  *Modulation index measurement
  *Displacement noise measurement
- Future plan

Why use MZM

KAGRA Main Interferometer (Main IFO)

Optical configuration called **Resonant Sideband Extraction** (**RSE**)



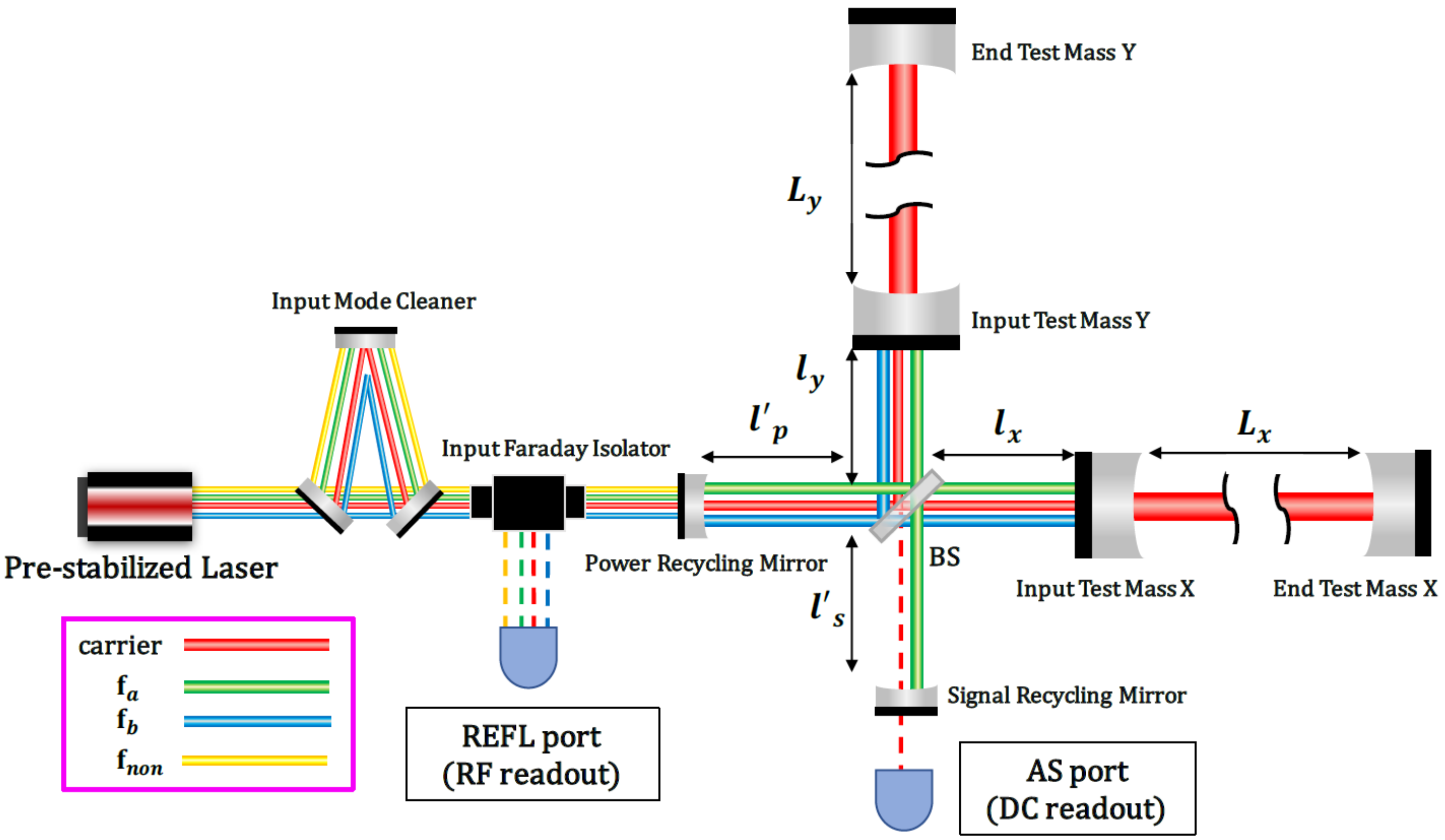
5 longitudinal **Degrees of Freedom** to be controlled

5 DOFs

- ARM:
  - CARM : FP common length
  - DARM : FP differential length
- Center:
  - MICH : Central Michelson
  - PRCL : PR cavity length
  - SRCL : SR cavity length

KAGRA Main Interferometer (Main IFO)

Optical configuration called **Resonant Sideband Extraction** (RSE)

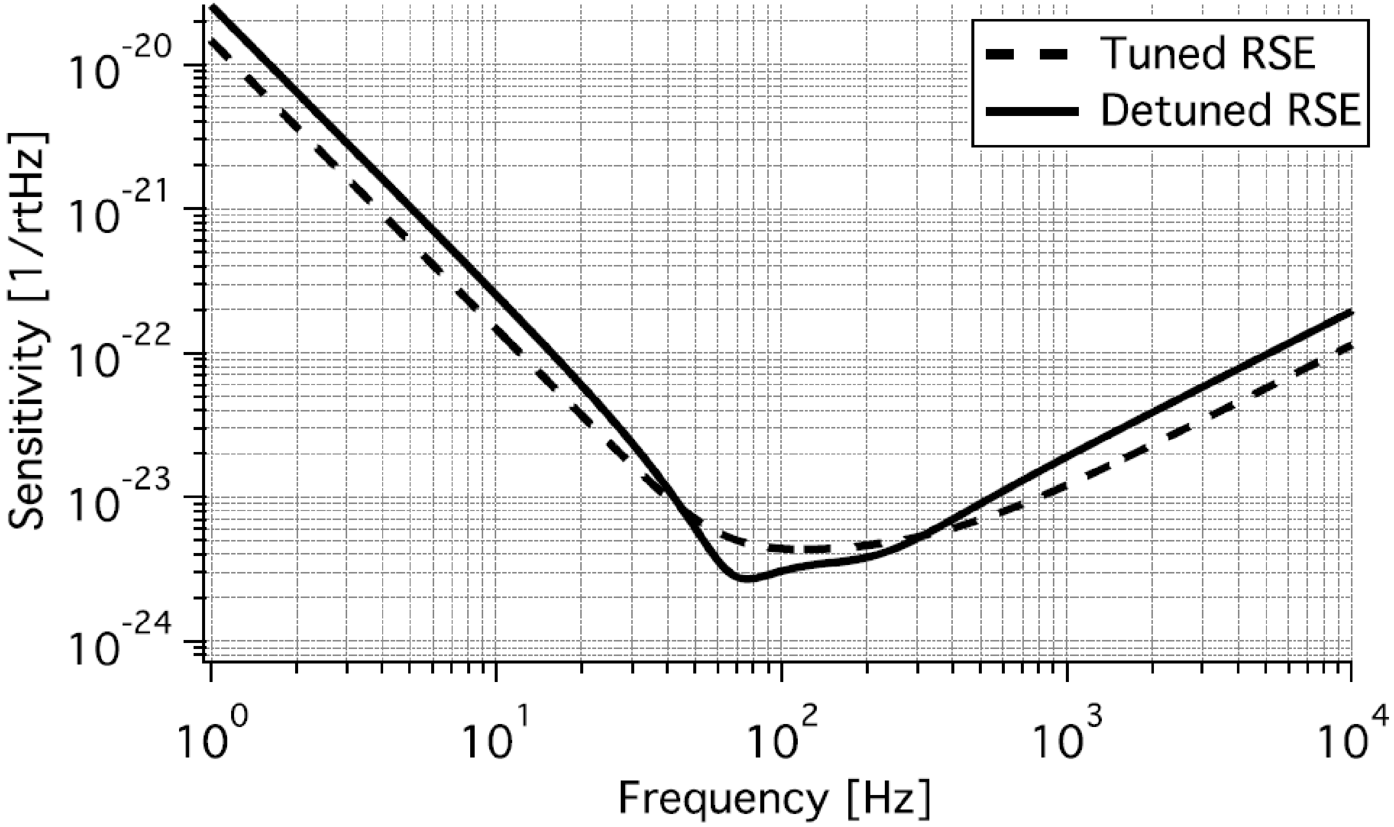


To obtain error signals of 5 DOFs, RF sidebands are necessary

	Frequency [MHz]	Resonant
f1	16.88	PRC&SRC
f2	45.02	PRC

Why use Mach-Zehnder Modulator (MZM)?

The primary target of KAGRA: Binary neutron star merger events, around 100Hz



RSE: limited by quantum noise

The operation mode can be switched from **RSE** to **DRSE** by adding an offset to the SRCL error signal.

Detuned RSE (DRSE): go beyond the quantum limit

- **Advantage:** increase the observation rate of Binary neutron star merger events
- **Disadvantage**: increase the couplings of noise includes **photo-detector noise** (PDN) and **oscillator phase noise** (OPN).

[Reference] : Class. Quantum Grav. 31 (2014) 095003

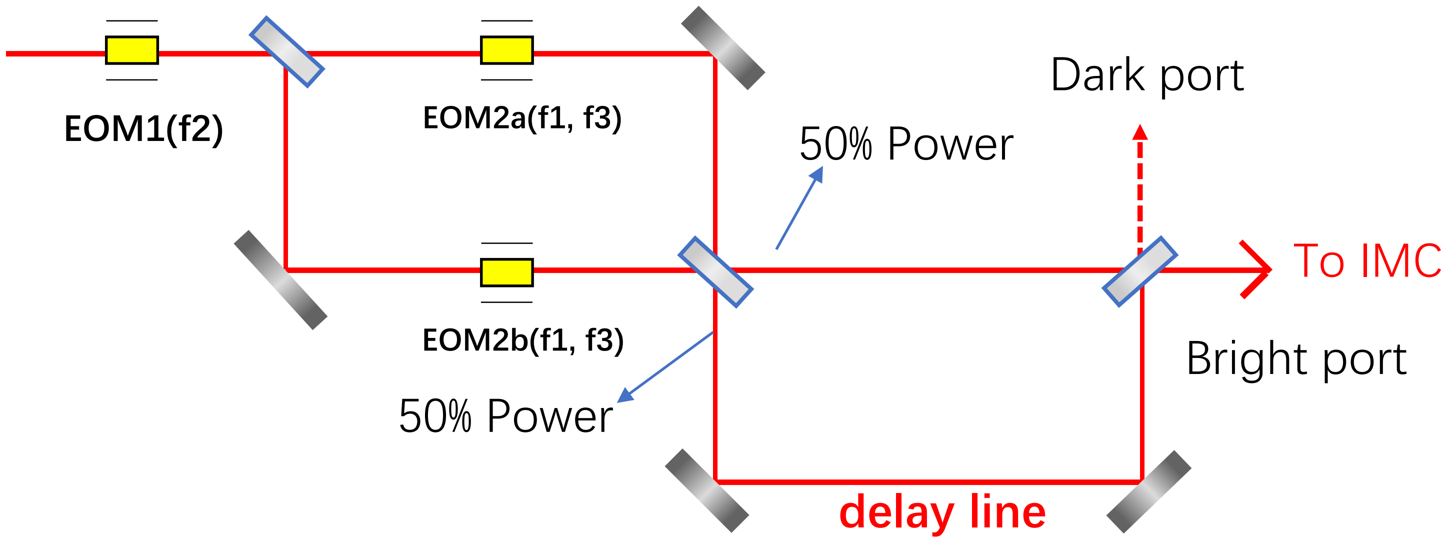
Why use Mach-Zehnder Modulator (MZM)?

- PDN/OPN originate from the tilt of upper and lower f1 sidebands.
- Solution: compensate the tilt by adding f1 amplitude modulation sidebands beforehand

Using an additional amplitude modulation (AM) sidebands to address the increased coupling of the PDN and OPN.

Mach-Zehnder Modulator (MZM) is proposed to achieve this

MZI Modulation system



Schematic view

Sidebands generated by MZM

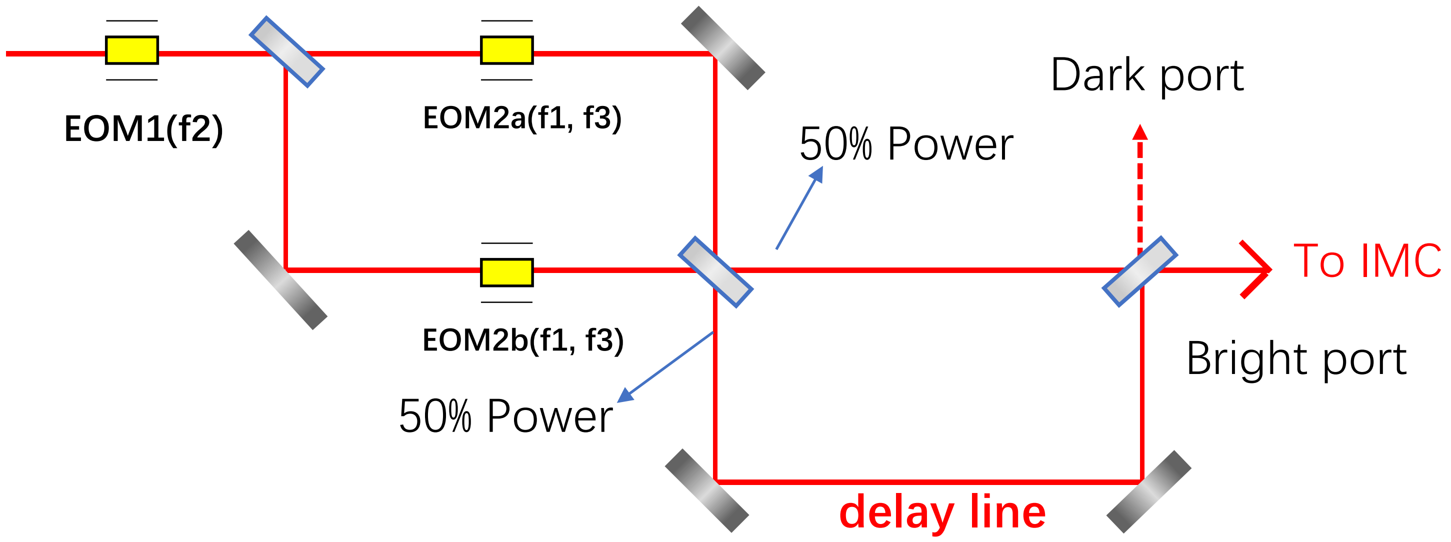
	Frequency [MHz]	Modulation type	
f1	16.88	PM and AM	
f2	45.02	PM	
f3	56.27	AM	

1^{st} MZI is locked at Mid-fringe

2^{nd} MZI is locked at Dark-fringe

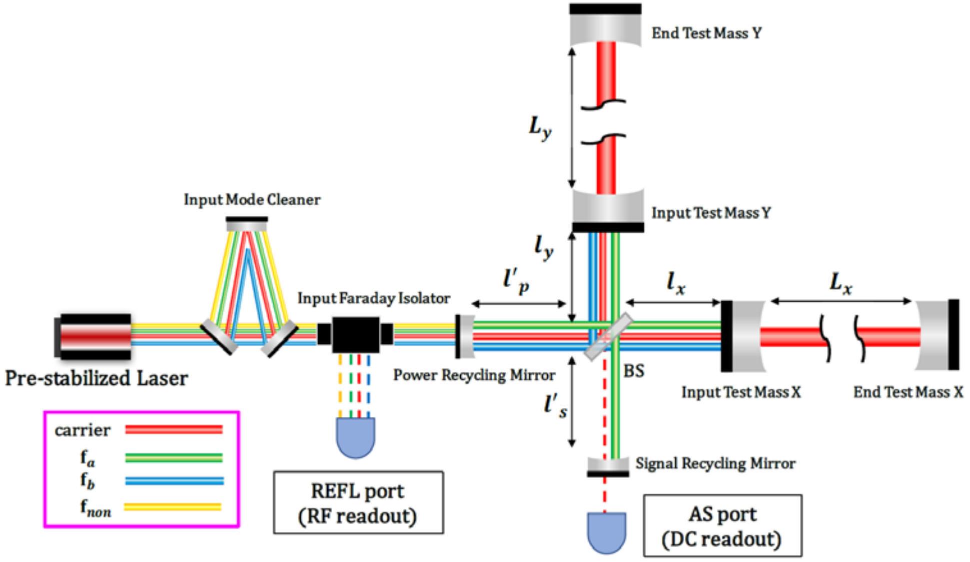
One more Advantage （f3 AM）: remove the signal couplings b/w the arm and center region of the main interferometer

MZI Modulation system



Sidebands generated by MZM

	Frequency [MHz]	Resonant
f1	16.88	PRC&SRC
f2	45.02	PRC
f3	56.27	Not resonant



One more Advantage （f3 AM）: remove the signal couplings b/w the arm and center region of the main interferometer

Modulation index

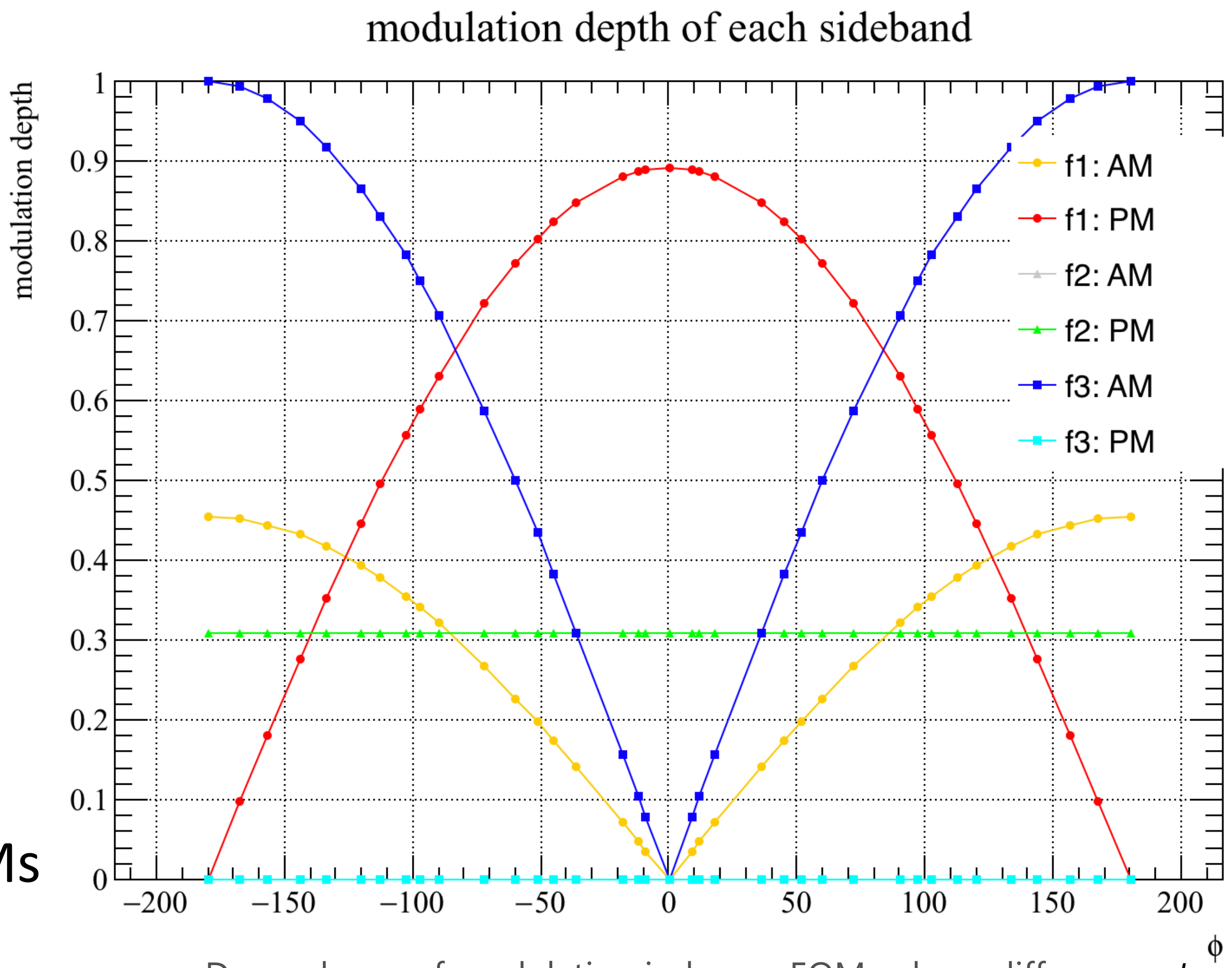
For a certain modulation frequency, field after MZM can be shown as：

$$E_{out} = E_0 e^{i\omega t}[1 + \Gamma \sin(\frac{\phi}{2}) \sin(\frac{\theta}{2}) \cos(\Omega_m t + \frac{\theta + \phi - \pi}{2})$$
$$+ i\Gamma \cos(\frac{\phi}{2}) \cos(\frac{\theta}{2}) \cos(\Omega_m t + \frac{\theta + \phi - \pi}{2})]$$

1st term: carrier field
2nd term: AM component
3rd term: PM component

ϕ is the phase difference applied between EOMs

θ is the phase difference introduced by delay-line，delay-line = 2.66m, f3 only has AM component (can realize by phase difference is pi, in this case

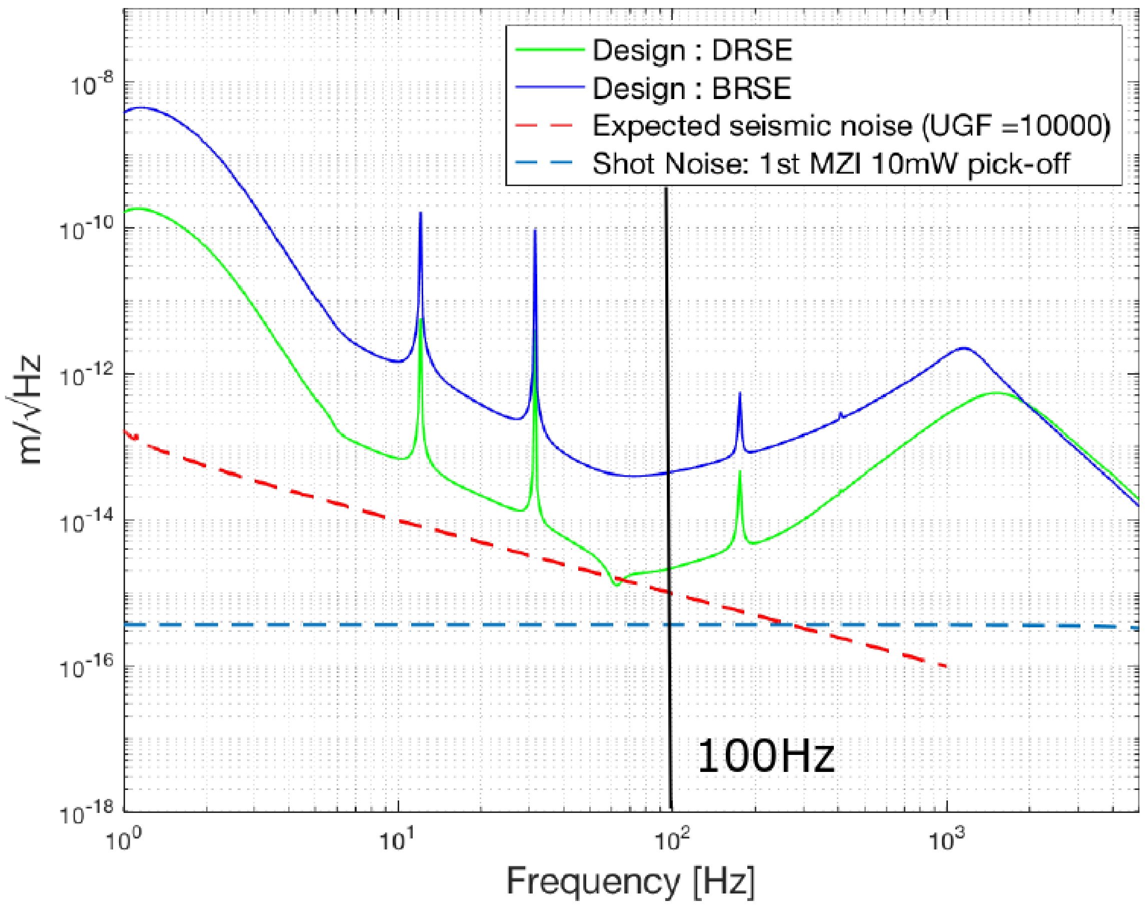


Dependence of modulation index on EOMs phase difference ϕ

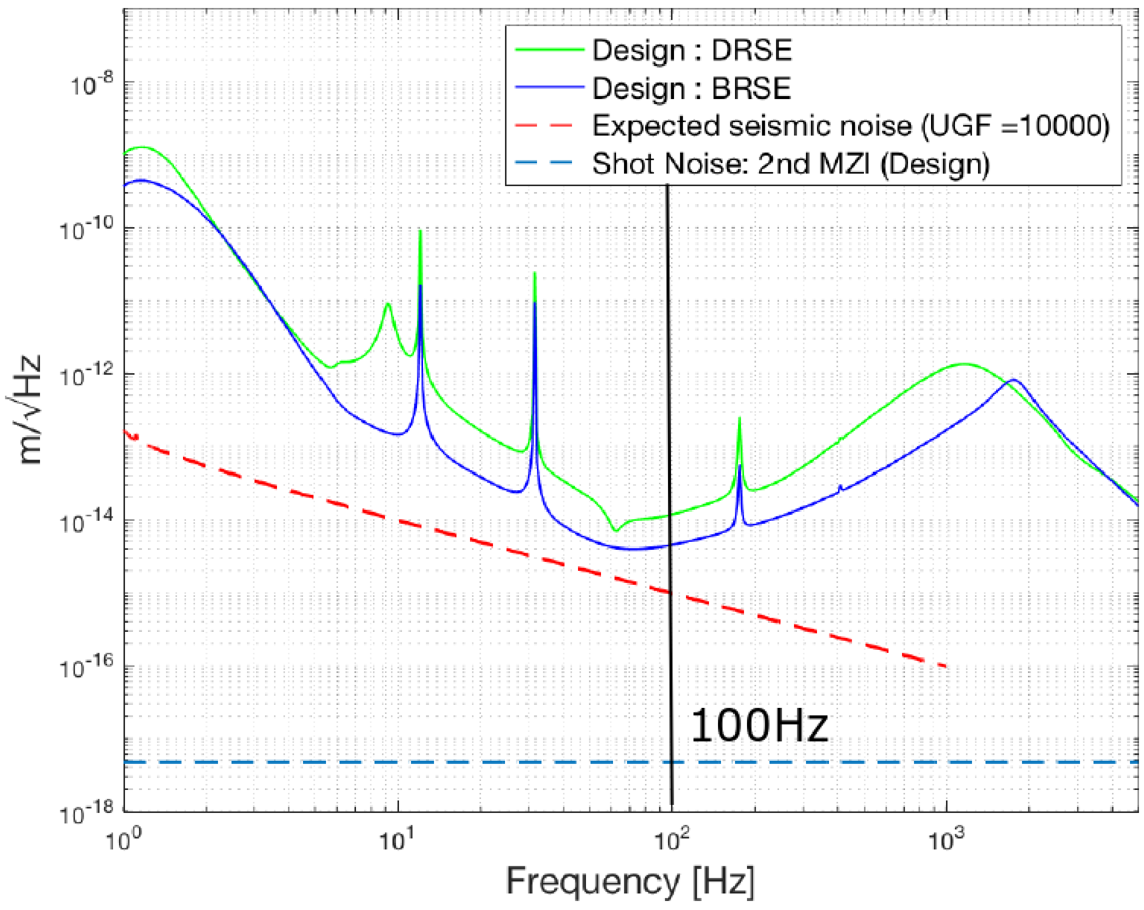
Displacement noise requirement

Displacement noise requirement

Displacement of optical paths in the MZIs is converted into sideband amplitude and phase noises ,and in the end, these noises couple into the DC fluctuation at the AS port (GW signal).



(a) 1st MZI

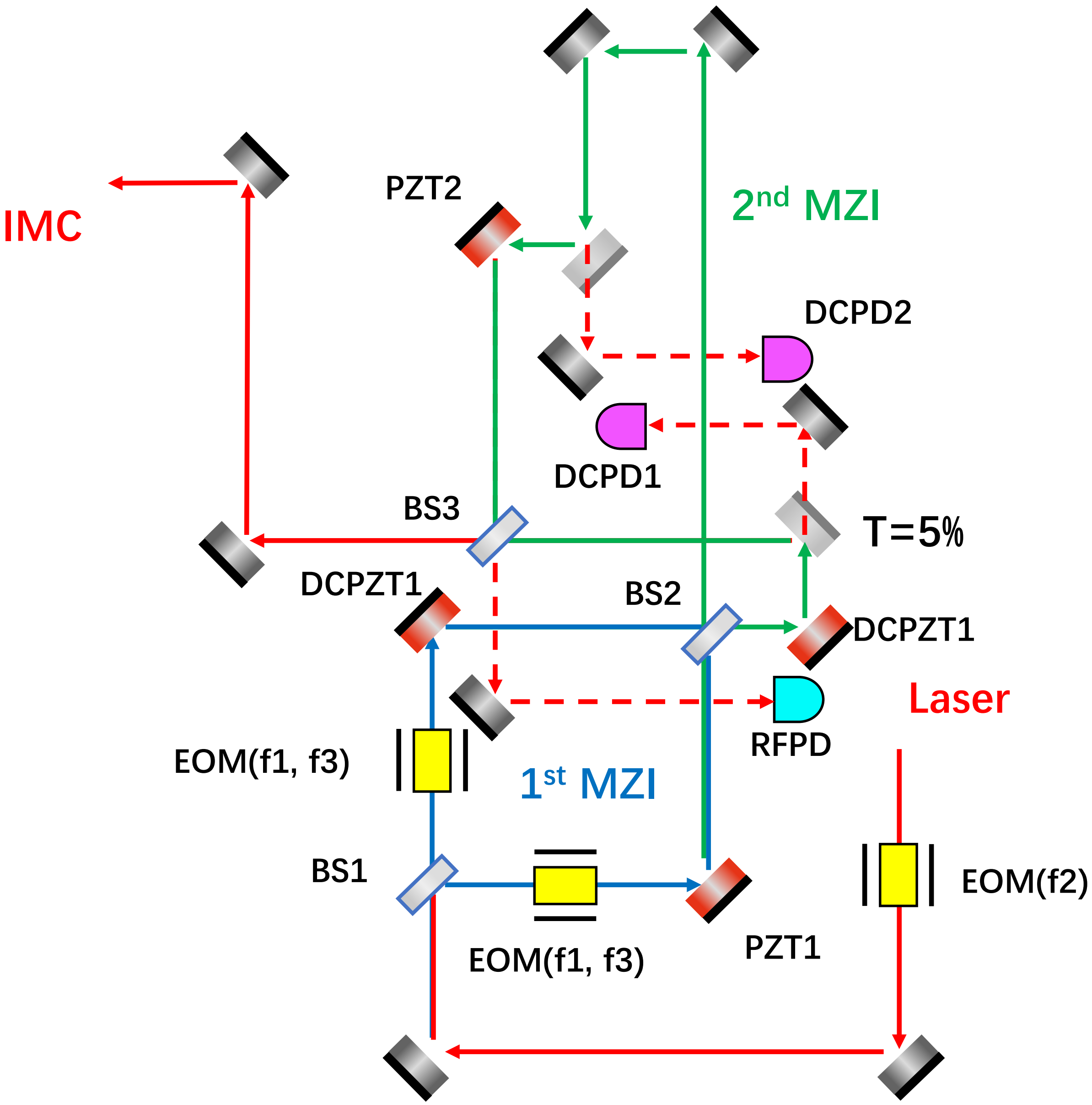


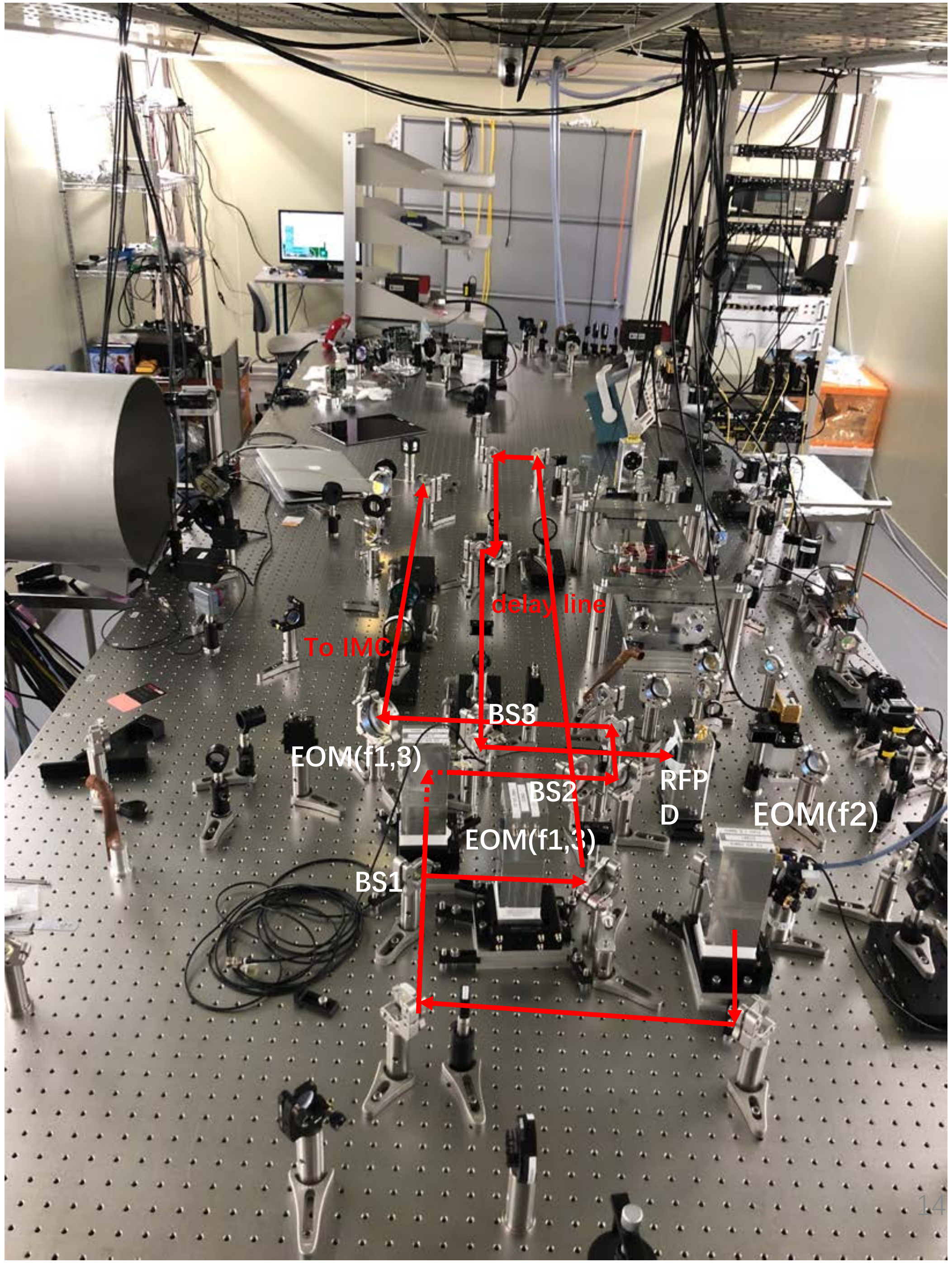
(b) 2nd MZI

Calculate by Yamakoh, code is Optickle, shown the feasibility of the MZM system

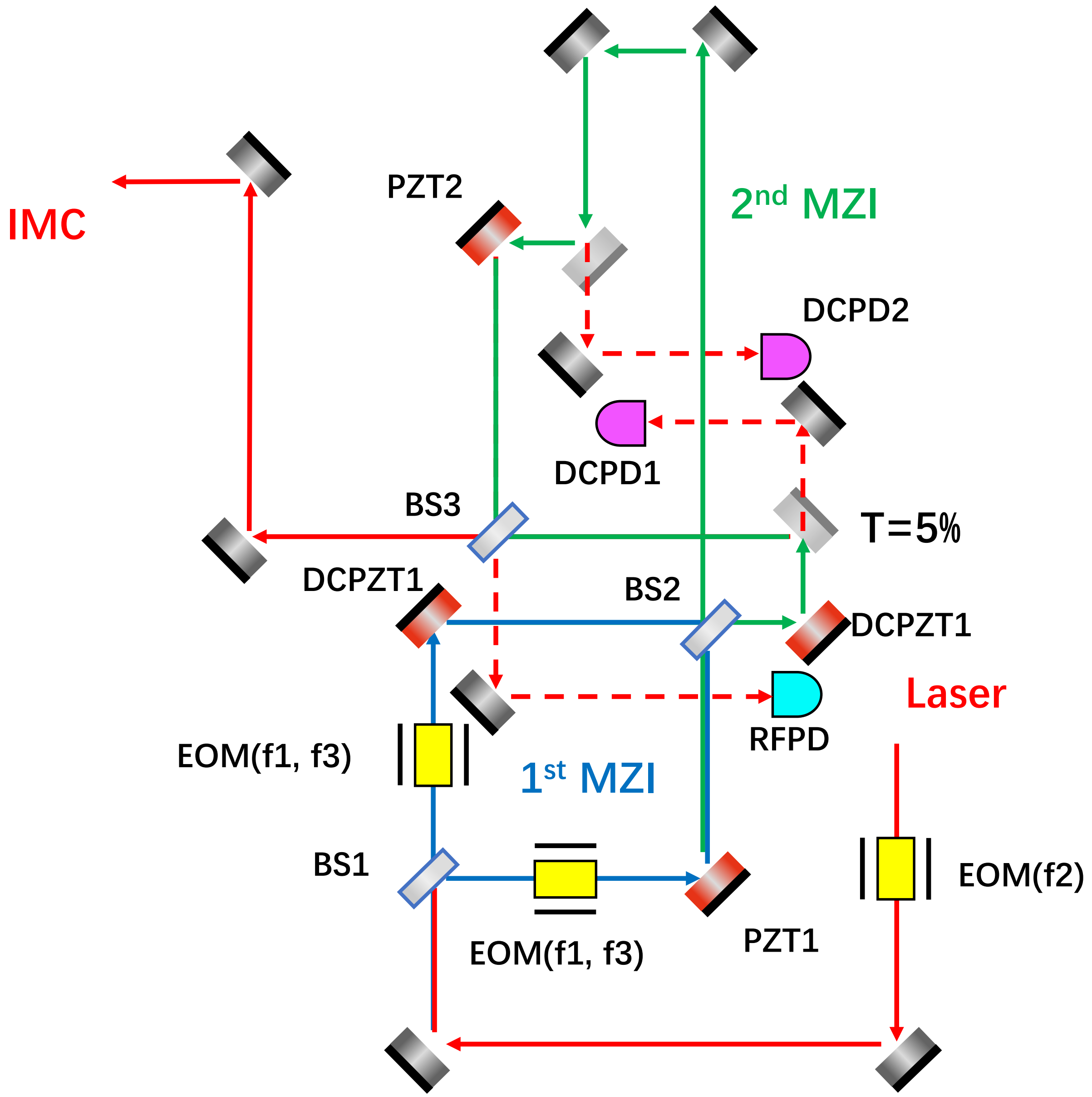
Experiment

Installation on the input optics





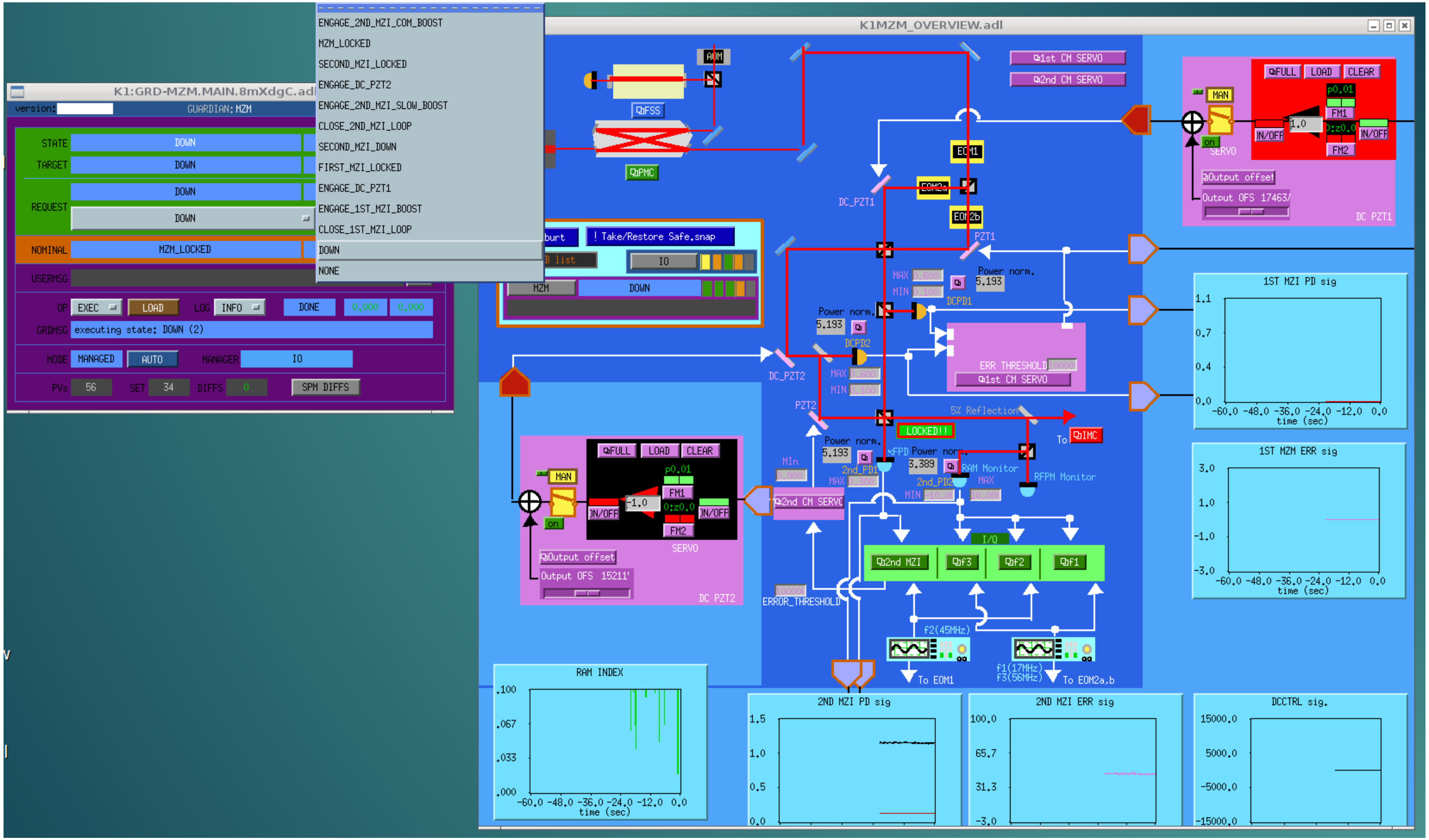
Installation on the input optics



- PZT: 2 PZTs for each MZI
- Servo: Common mode servo
- Connected to KAGRA digital system
- Automatically controlled by guardian

Control

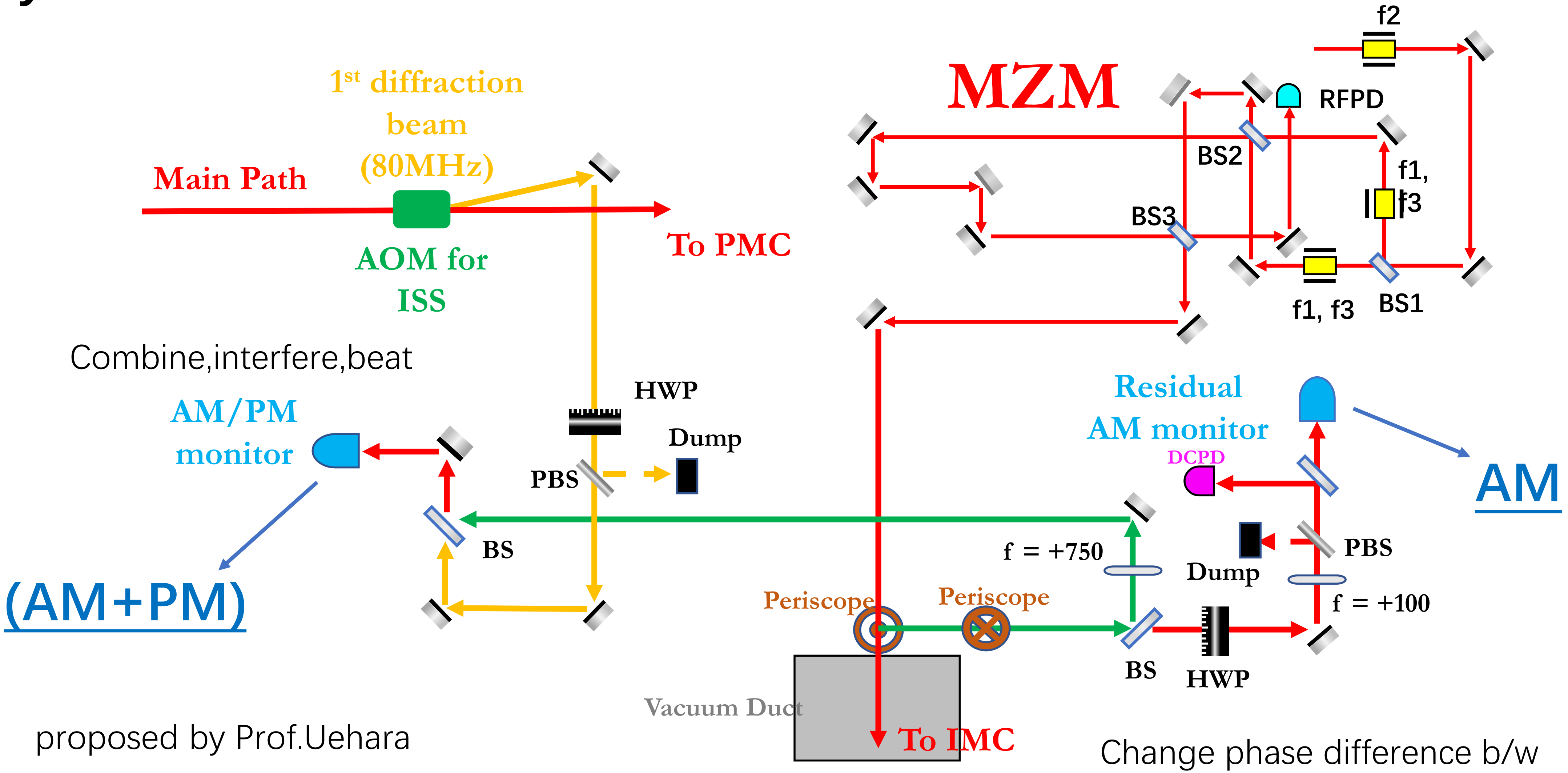
Fully commissioned including automation



Both 2 MZIs can be locked by guardian remotely

Modulation index measurement

System of Modulation index Measurement



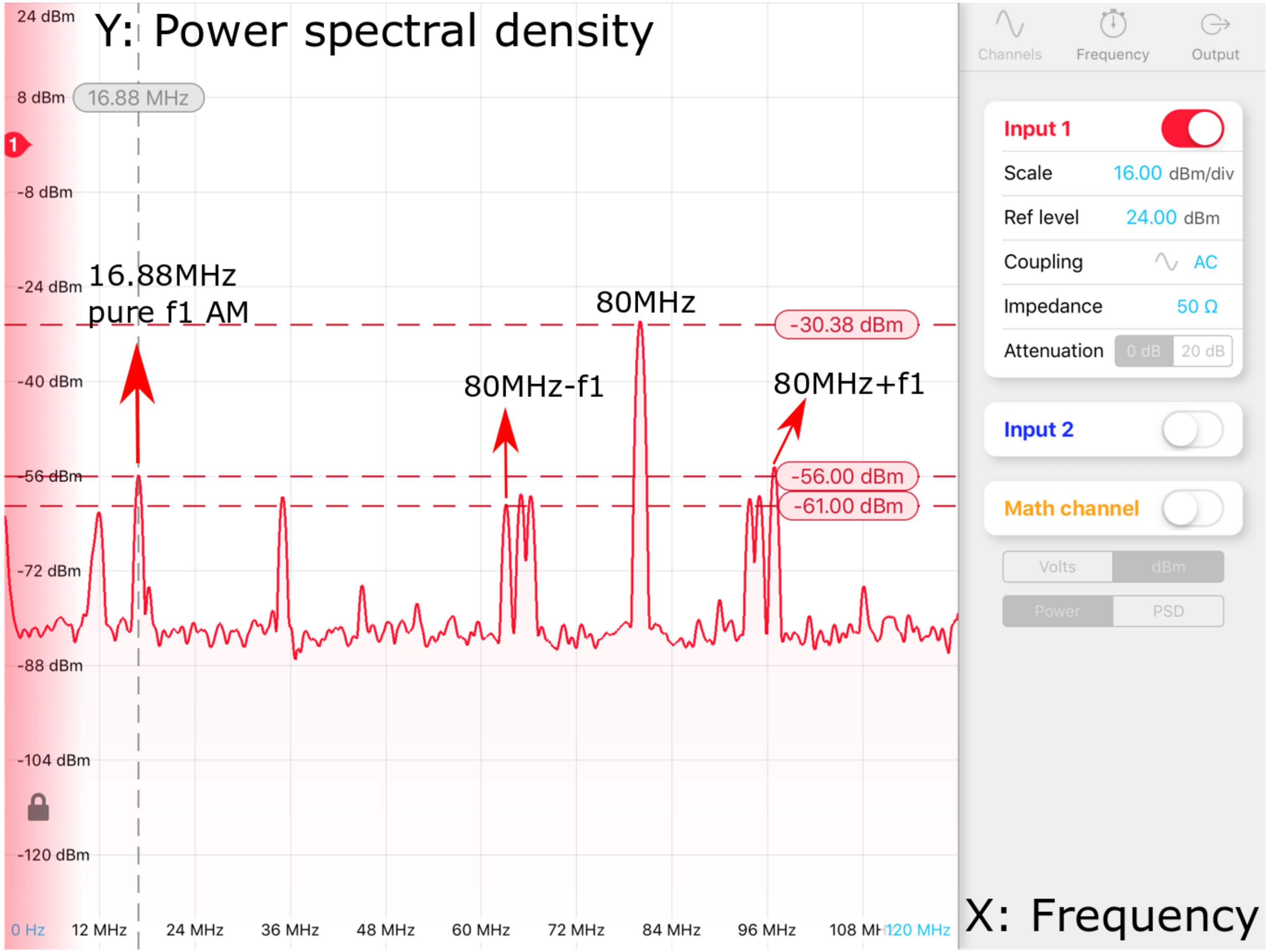
proposed by Prof.Uehara

Change phase difference b/w EoMs by changing the cable length b/w two EoMs

https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=9602

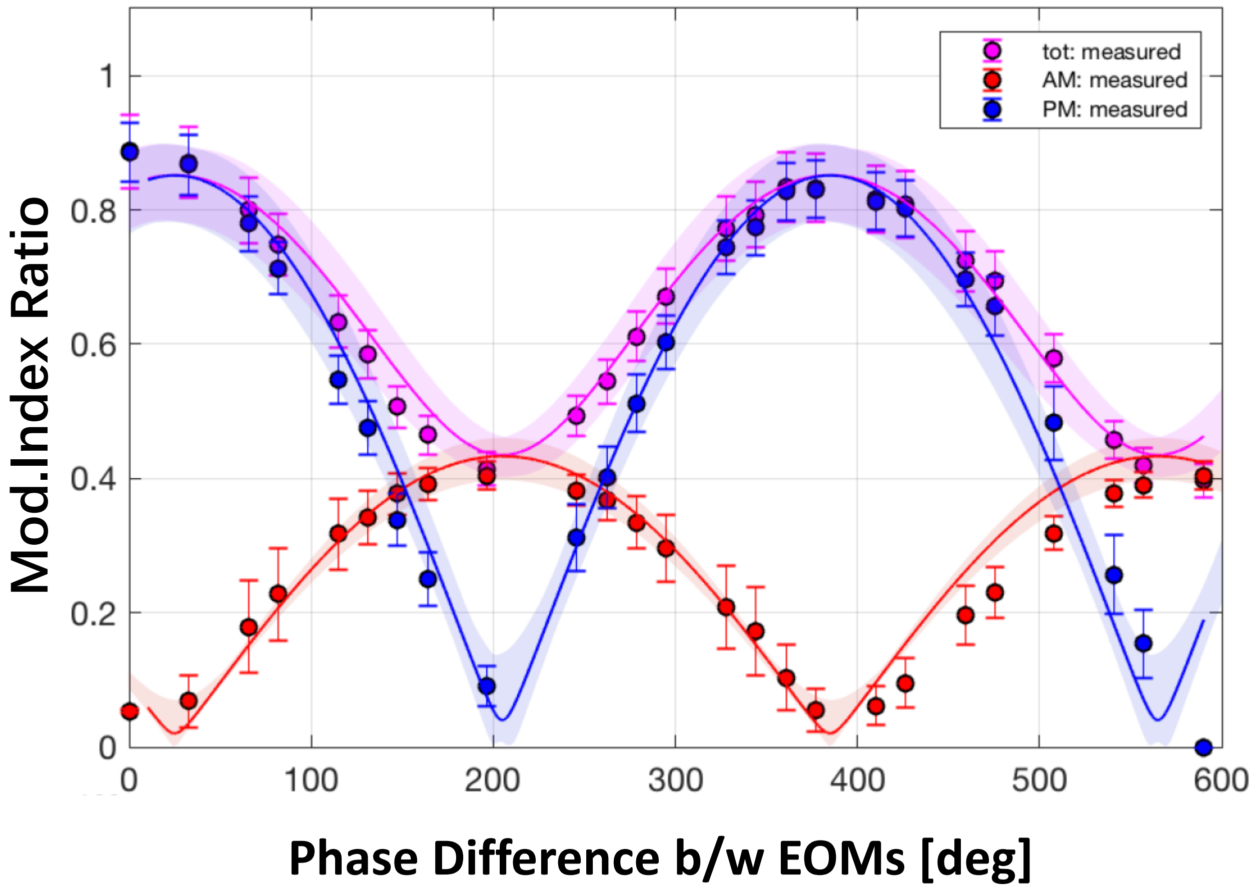
Modulation index measurement

<ins>Calibrate the measurements of AM & PM monitor into AM & PM index</ins>

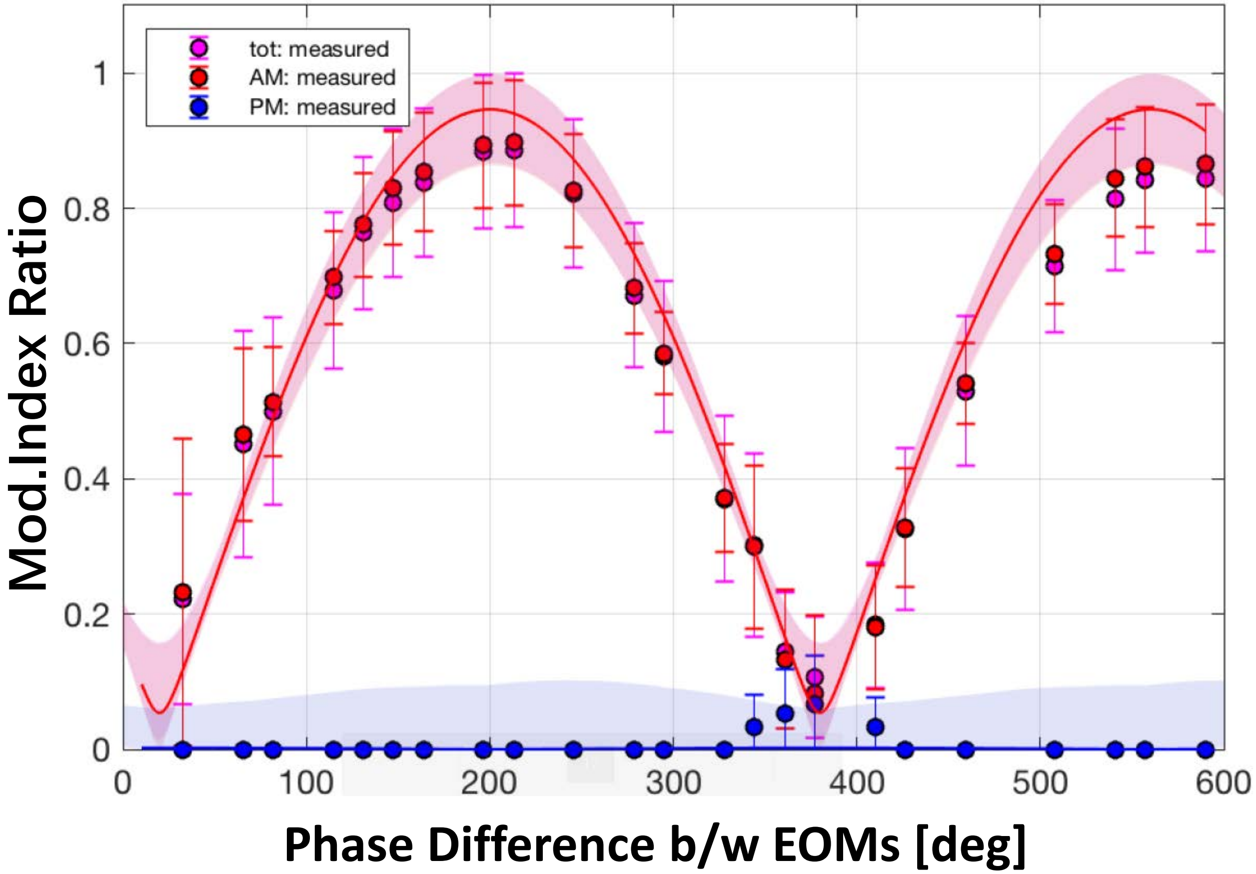


80deg_f1

Measurement results



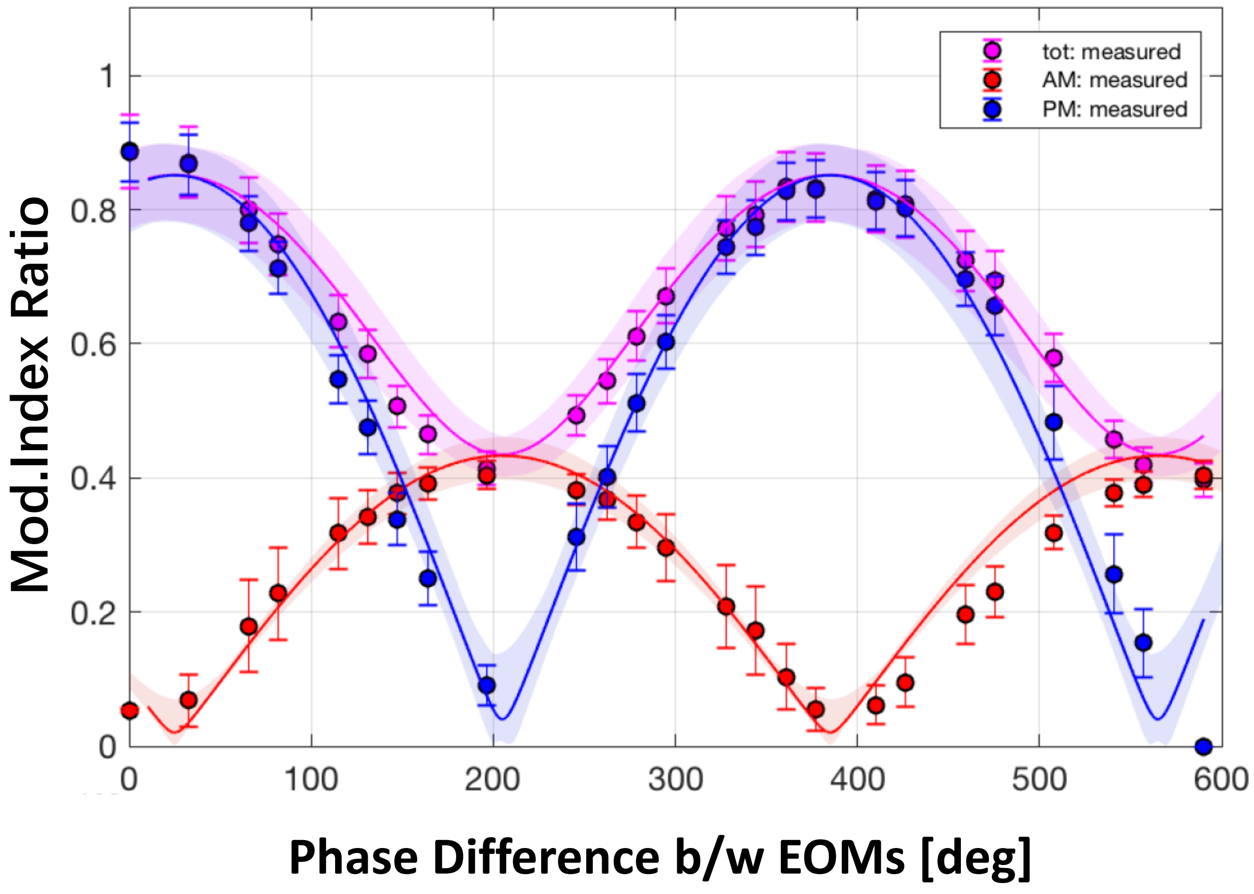
(f1)



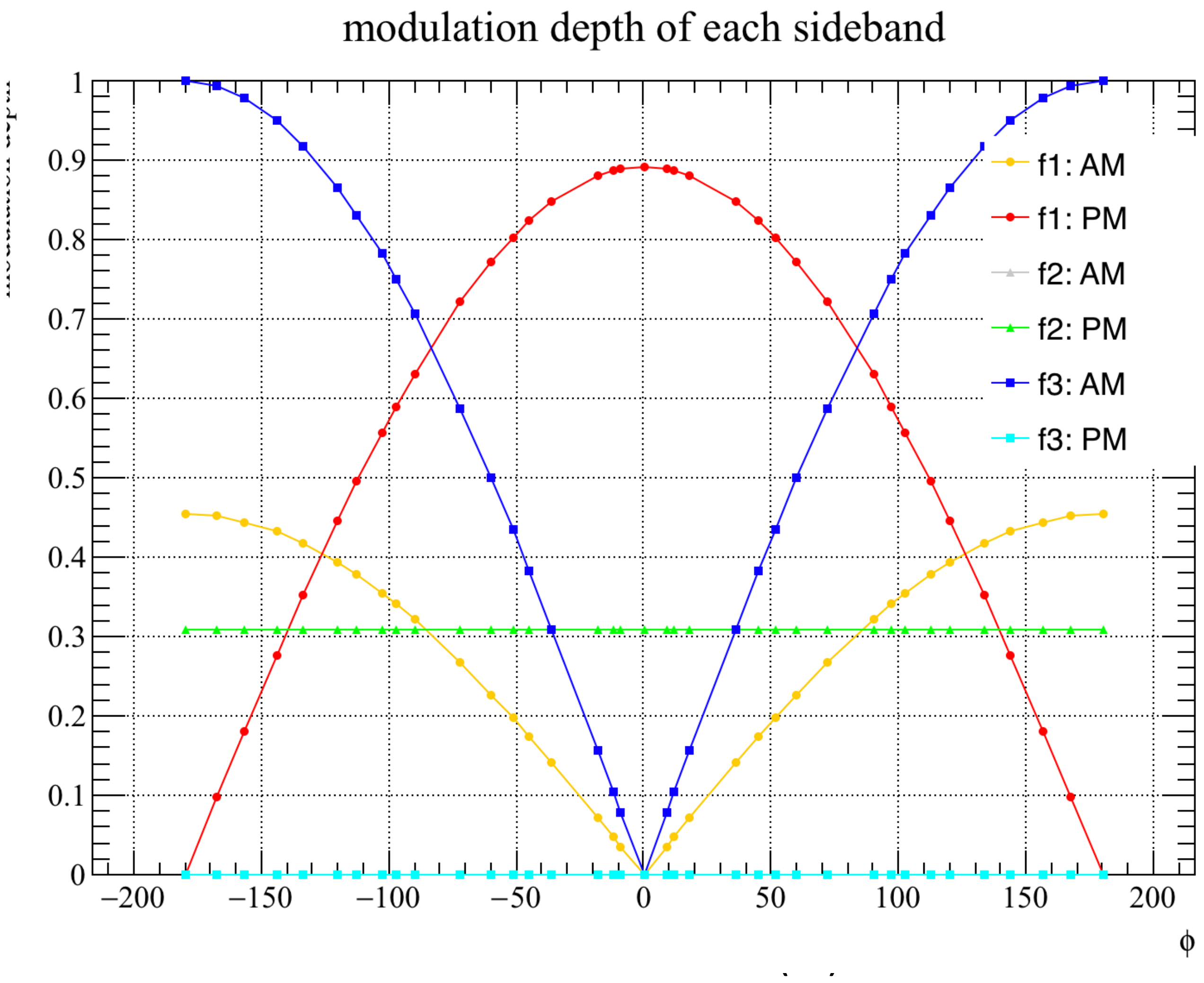
(f3)

Means the proof-of-principle experiments were successful and the measurements demonstrated the theory.

Measurement results



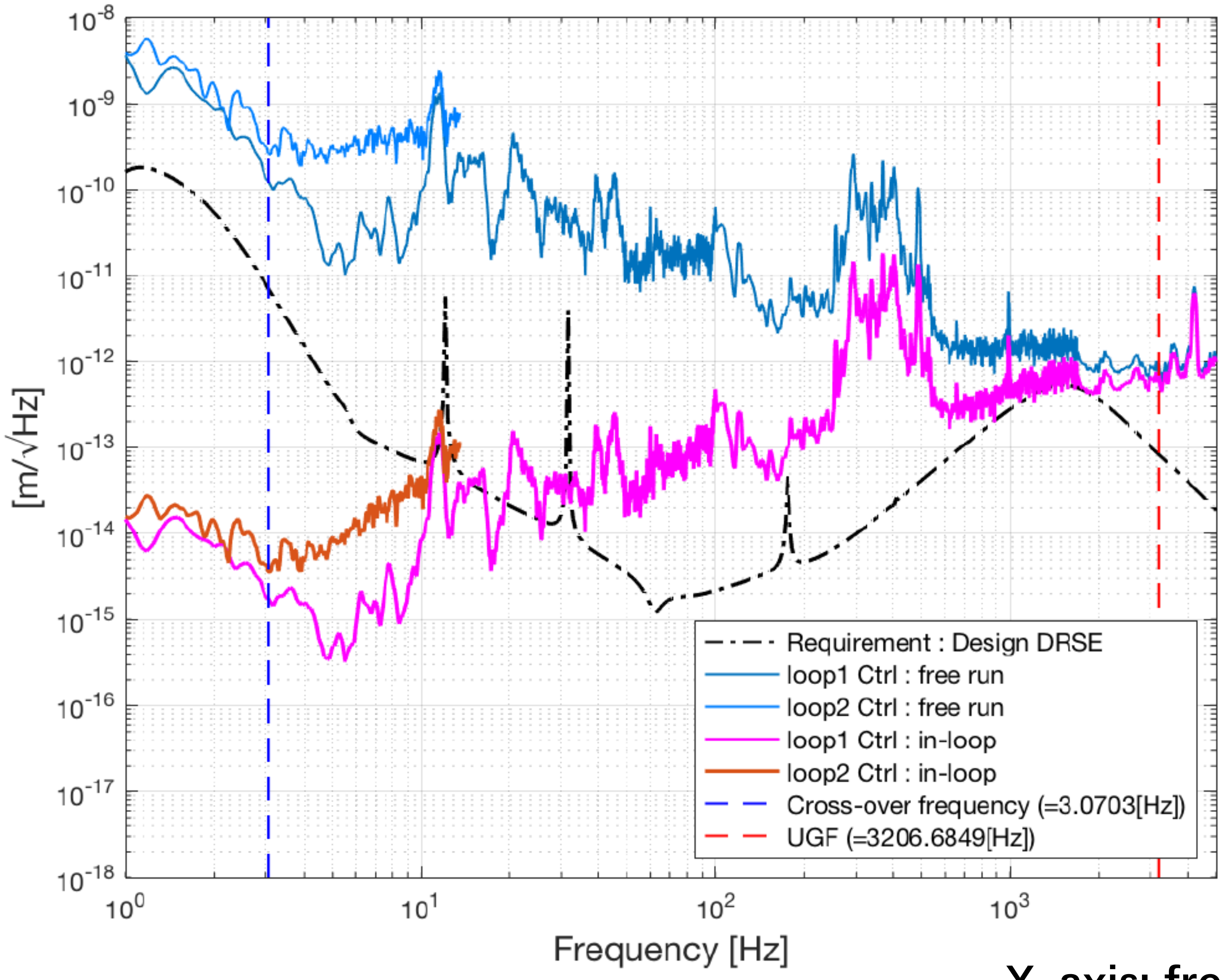
(f1)



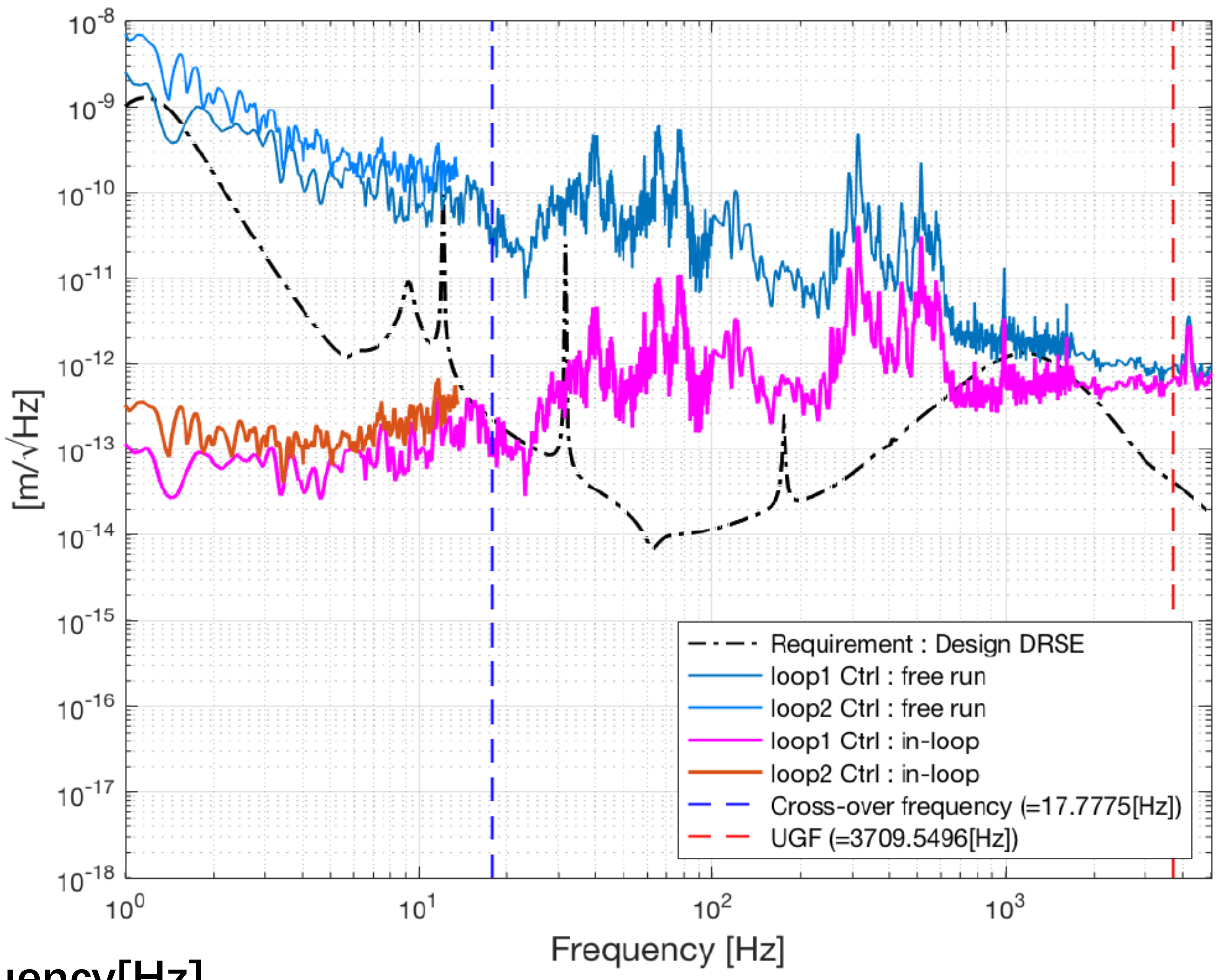
Means the proof-of-principle experiments were successful and the measurements demonstrated the theory.

Displacement noise

Displacement Noise Measurement



1st MZI

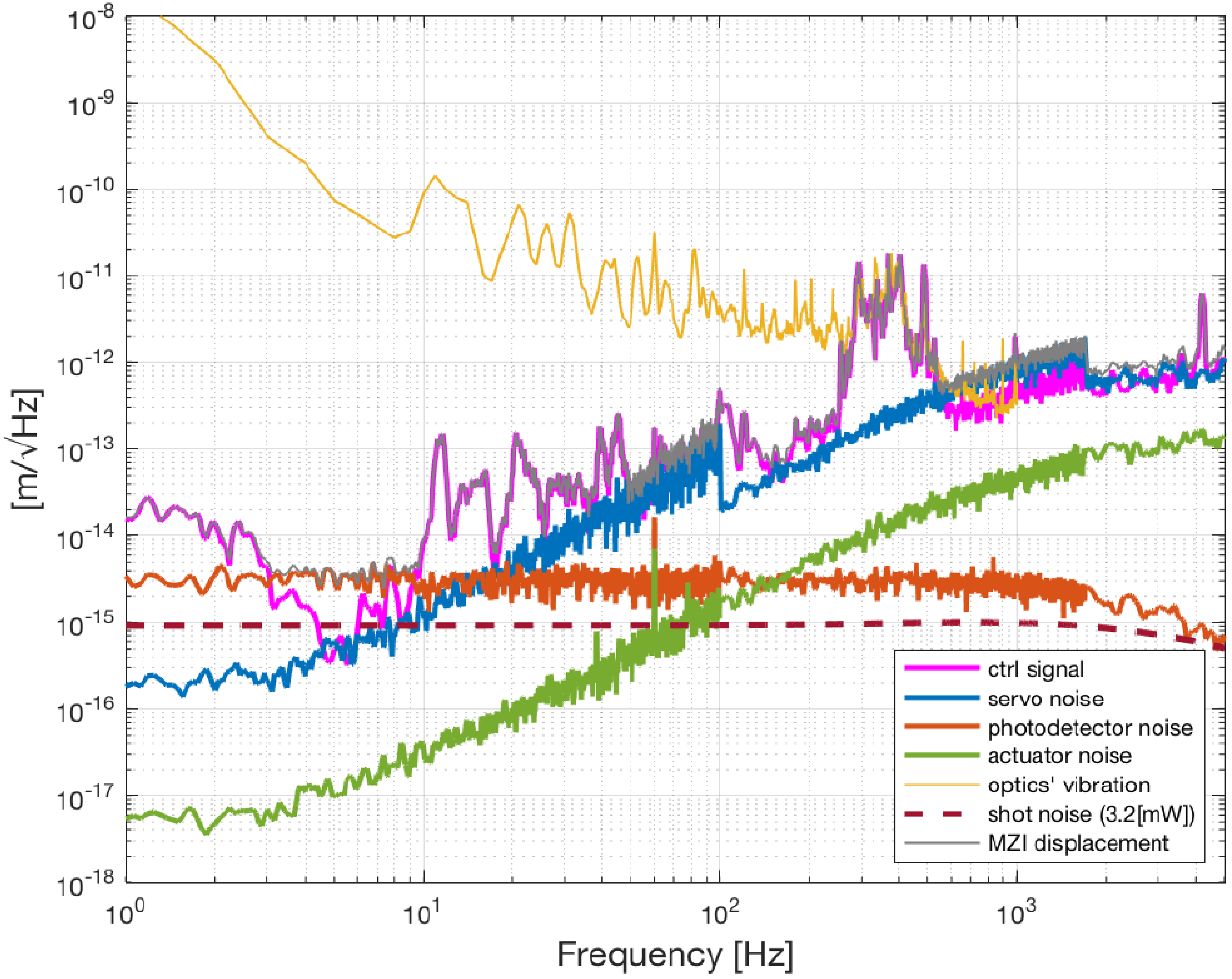


2nd MZI

X-axis: frequency[Hz]
Y-axis: [m/rtHz]

It did not satisfy the requirement

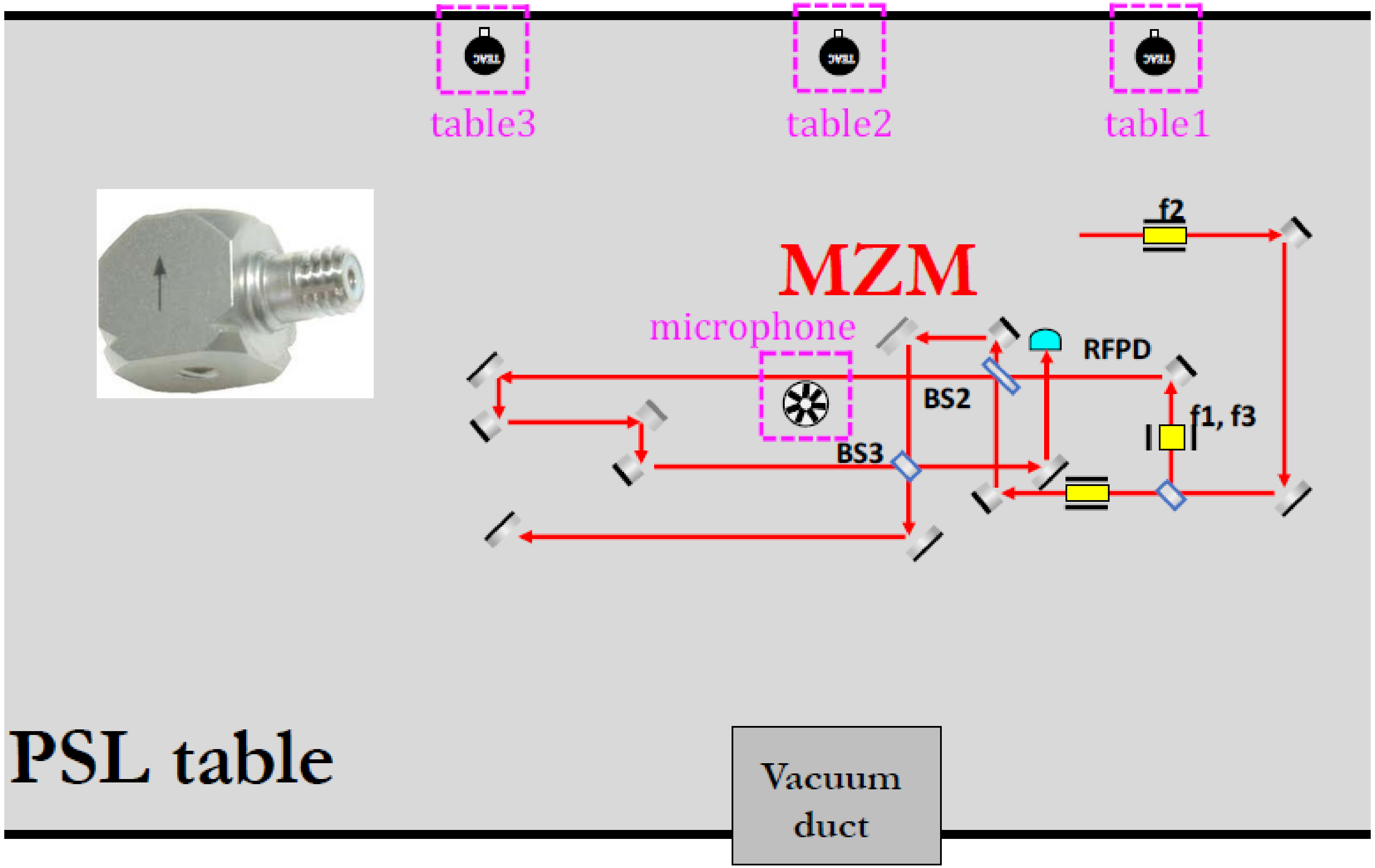
Displacement Noise budget



1st MZI noise budget

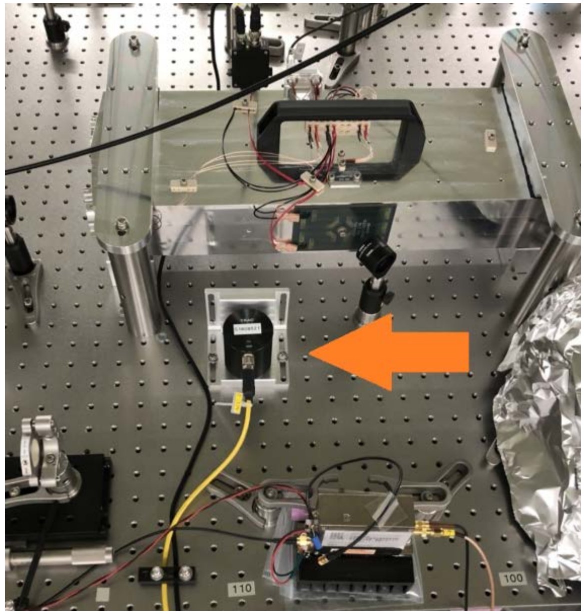
- servo noise
- actuator noise
- photodetector dark noise
- Optics's vibration

Coherence analysis.

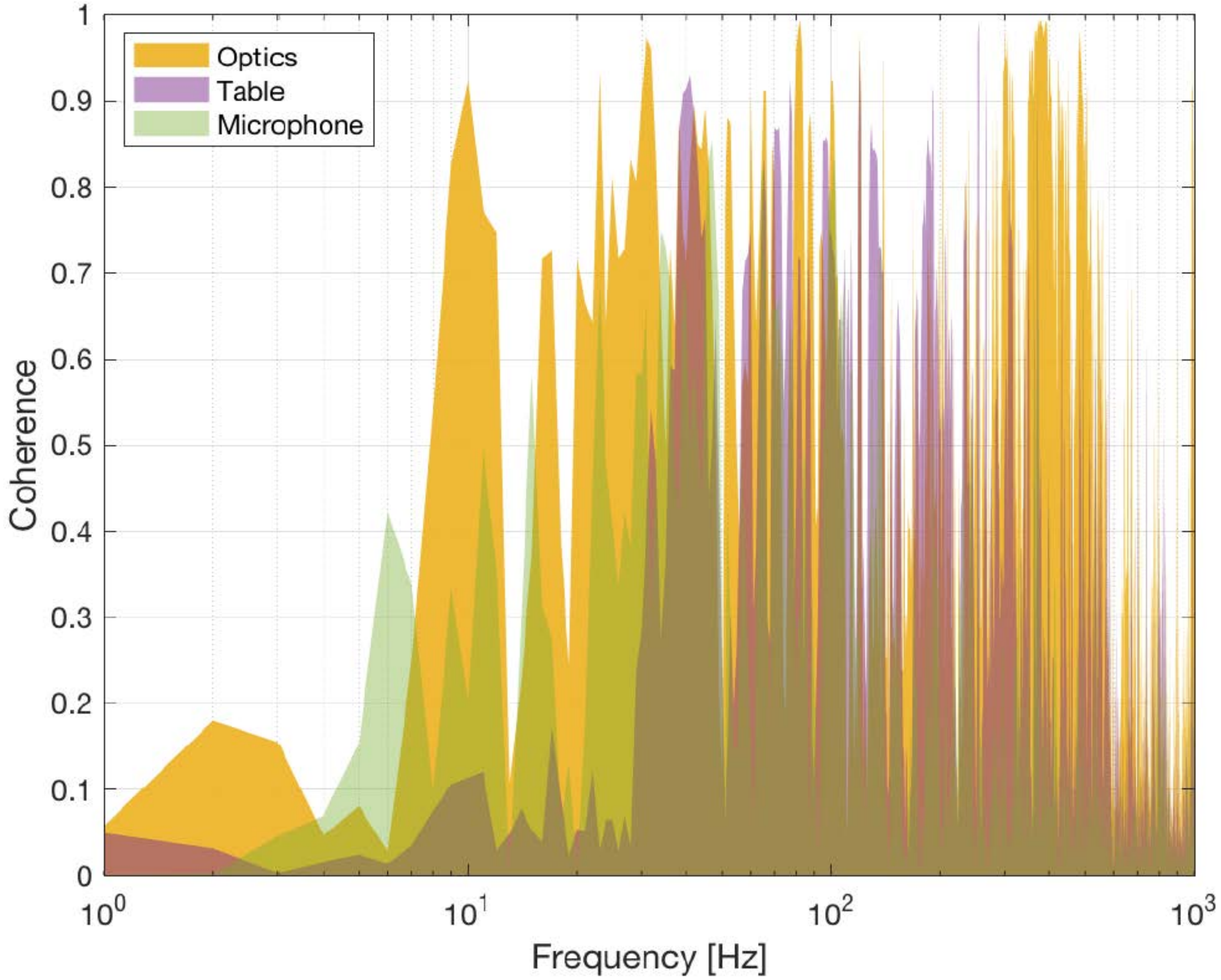


PEM sensors

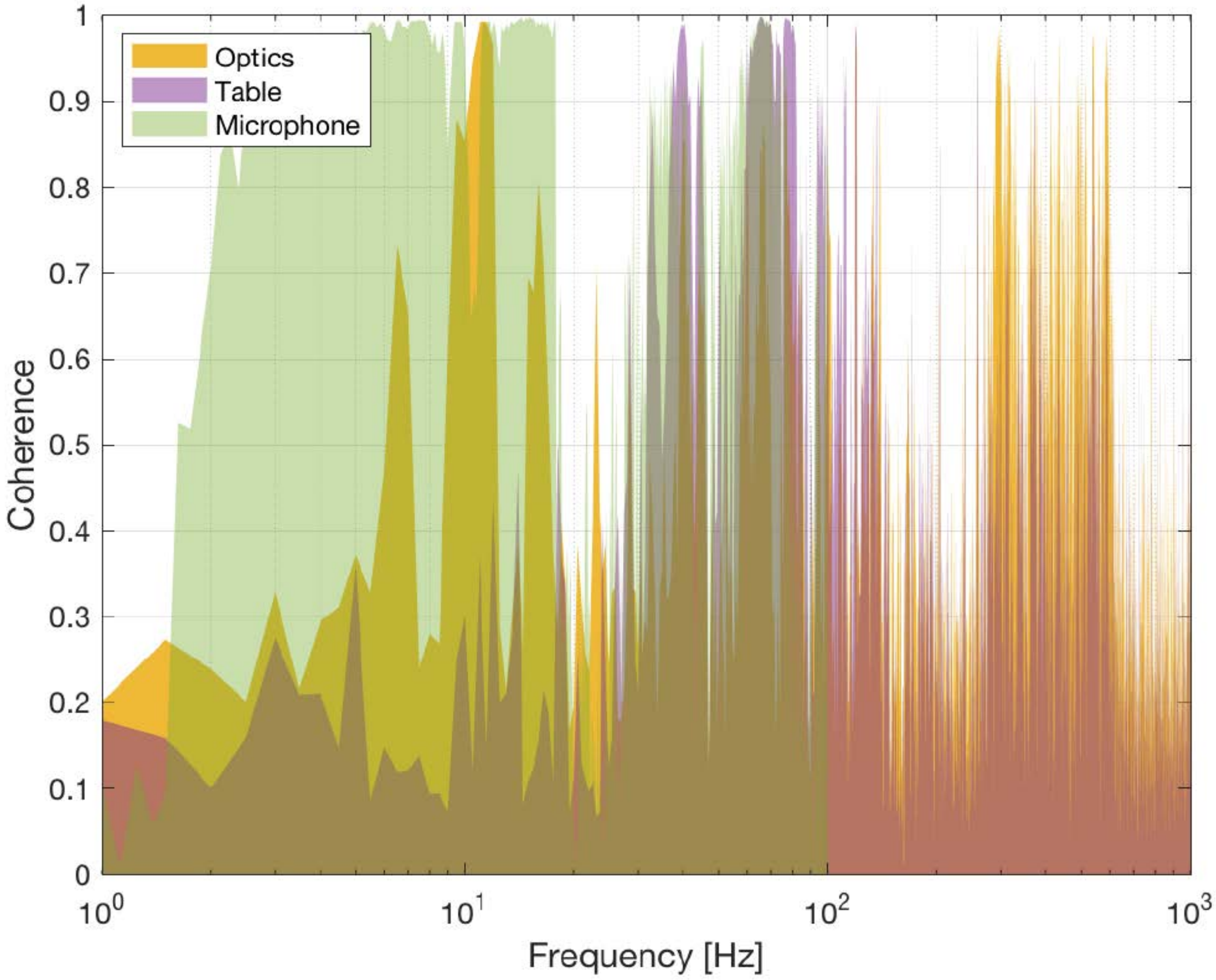
- Accelerometer
- Microphone



Coherence analysis.



1st MZI



2nd MZI

Coherence function between MZIs displacement and signals of environmental monitros

Conclusion and Future plan

Conclusion:

- Demonstrated the basic function of MZM
- The current setup did not meet the noise requirement
- Dominant noise sources at each frequency were understood

Future R&D ideas:

- Replacement of the pedestals and holders with more rigid ones
- Use of the monolithic optics
- Put the optical paths in vacuum
- Make 2MZI smaller

END