Development of a signal amplification technique using nonlinear optical effects for next-generation gravitational wave detectors

Kaido Suzuki, Ken-ichi Harada, Sotatsu Otabe, Kentaro Somiya

Tokyo Institute of Technology

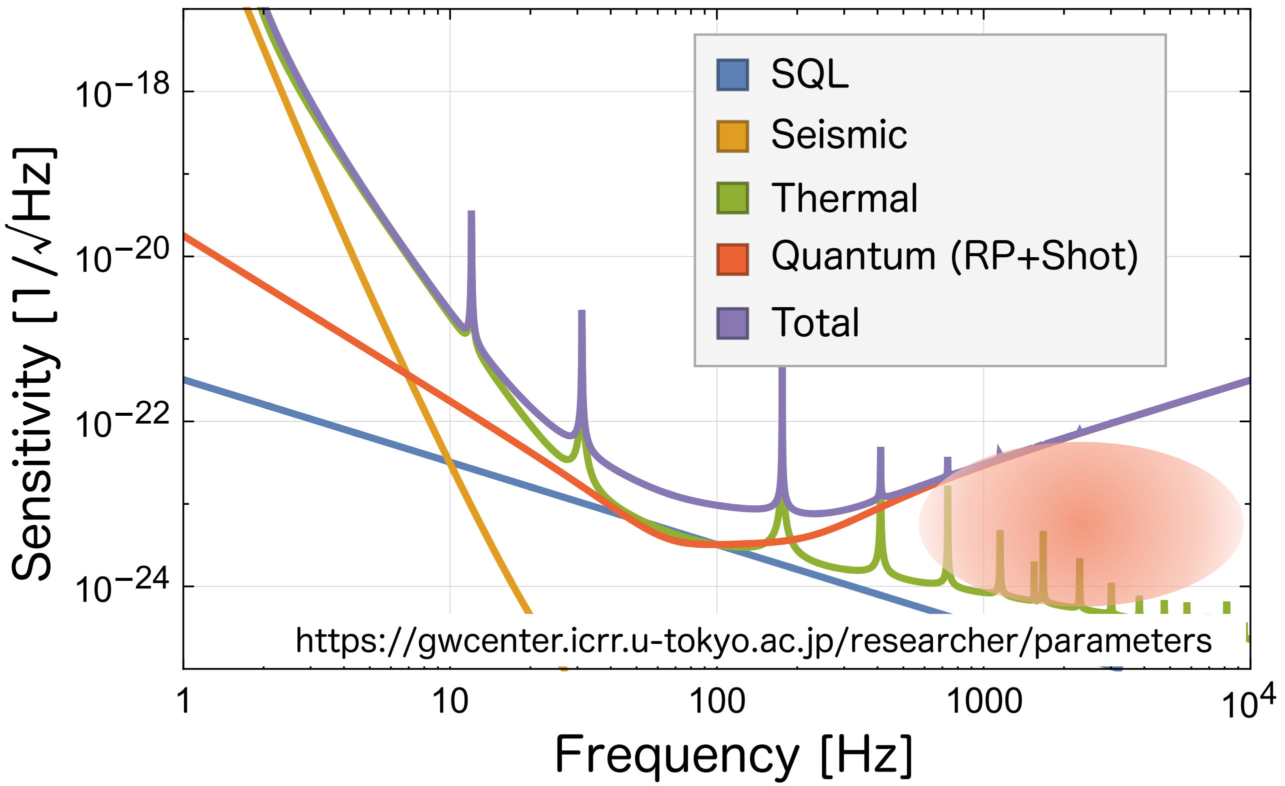
2023-5-26 (Fri)

Background

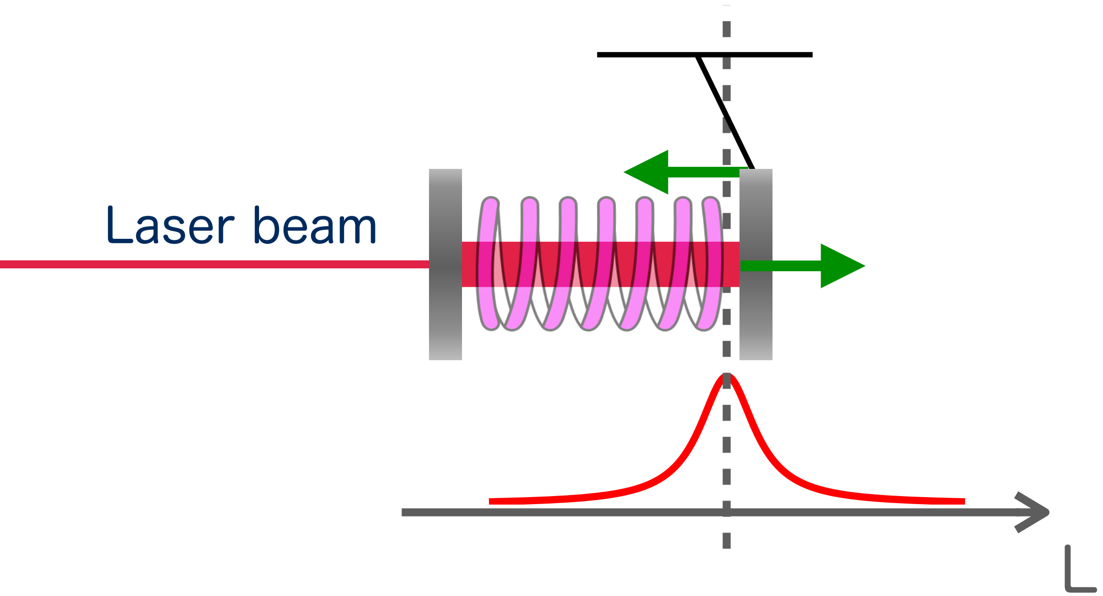
- Bandwidth limitation
  - ➡ High frequencies are limited by shot noise
- New method
  - ➡ Signal amplification with optical spring & intracavity OPA

Phys Lett A, Vol. 380, No. 4, pp. 521–524, 2016

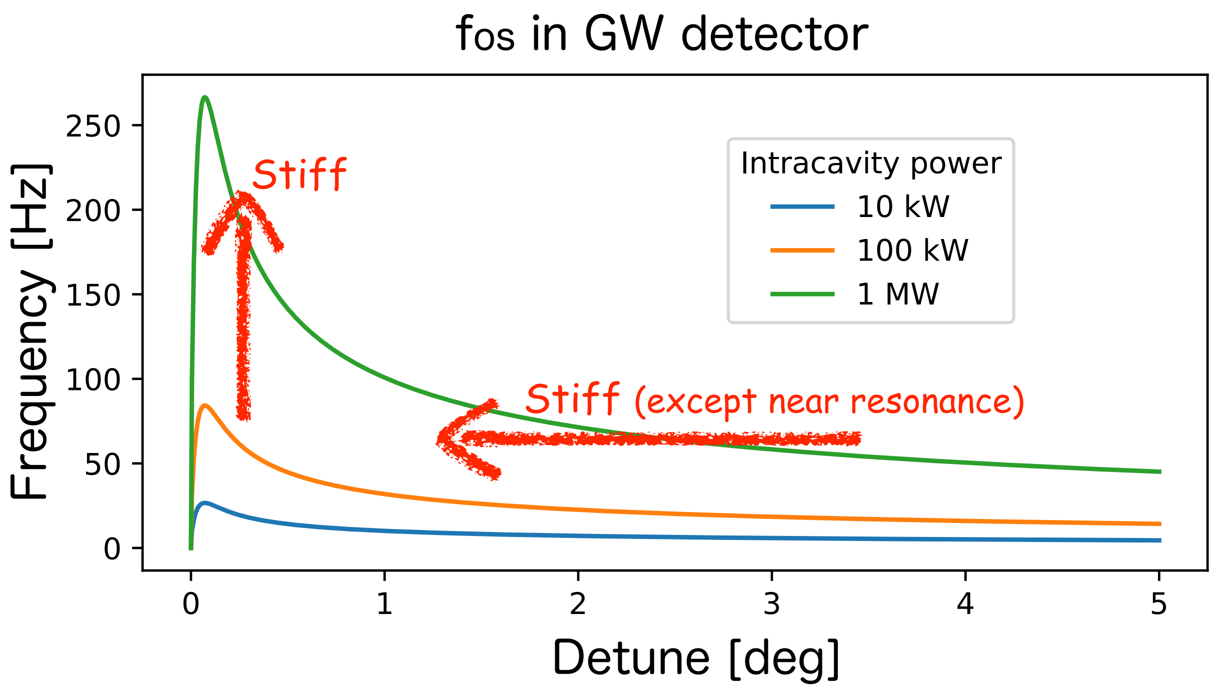
KAGRA sensitivity



Optical spring (OS)



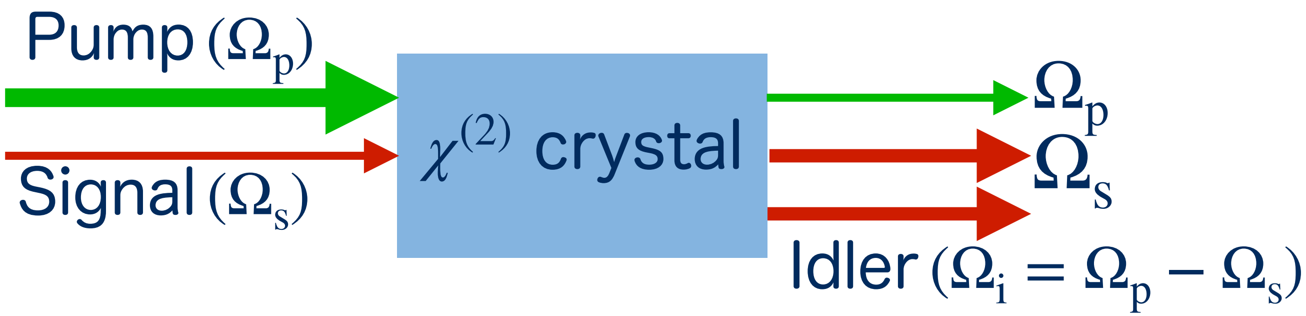
- Phase modulation signal is converted to amplitude modulation in a detuned cavity
- Mirror-laser interaction creates a "spring"



- GW signal is amplified at around optical spring resonance (f_{OS})
  - ➡ BNS merger at 3~4kHz
  - ➡ KAGRA: $f_{\mathrm{OS}} \simeq 50\,\mathrm{Hz}$
  - ➡ Parametric amplification

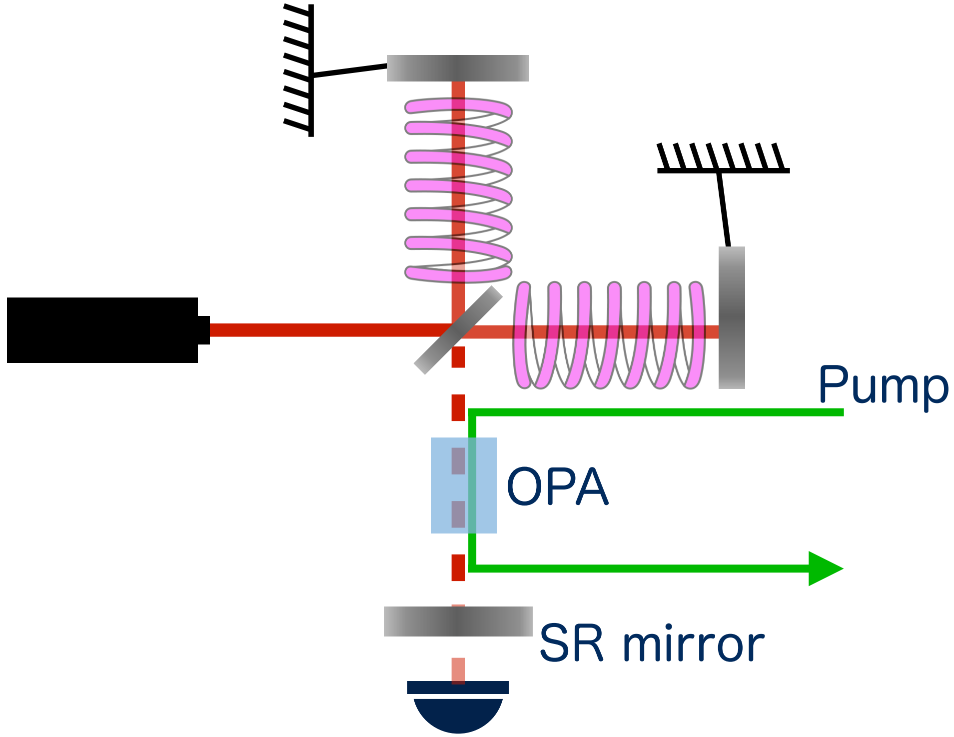
Optical parametric amplification (OPA)

- Nonlinear optical effect with $\chi^{(2)}$

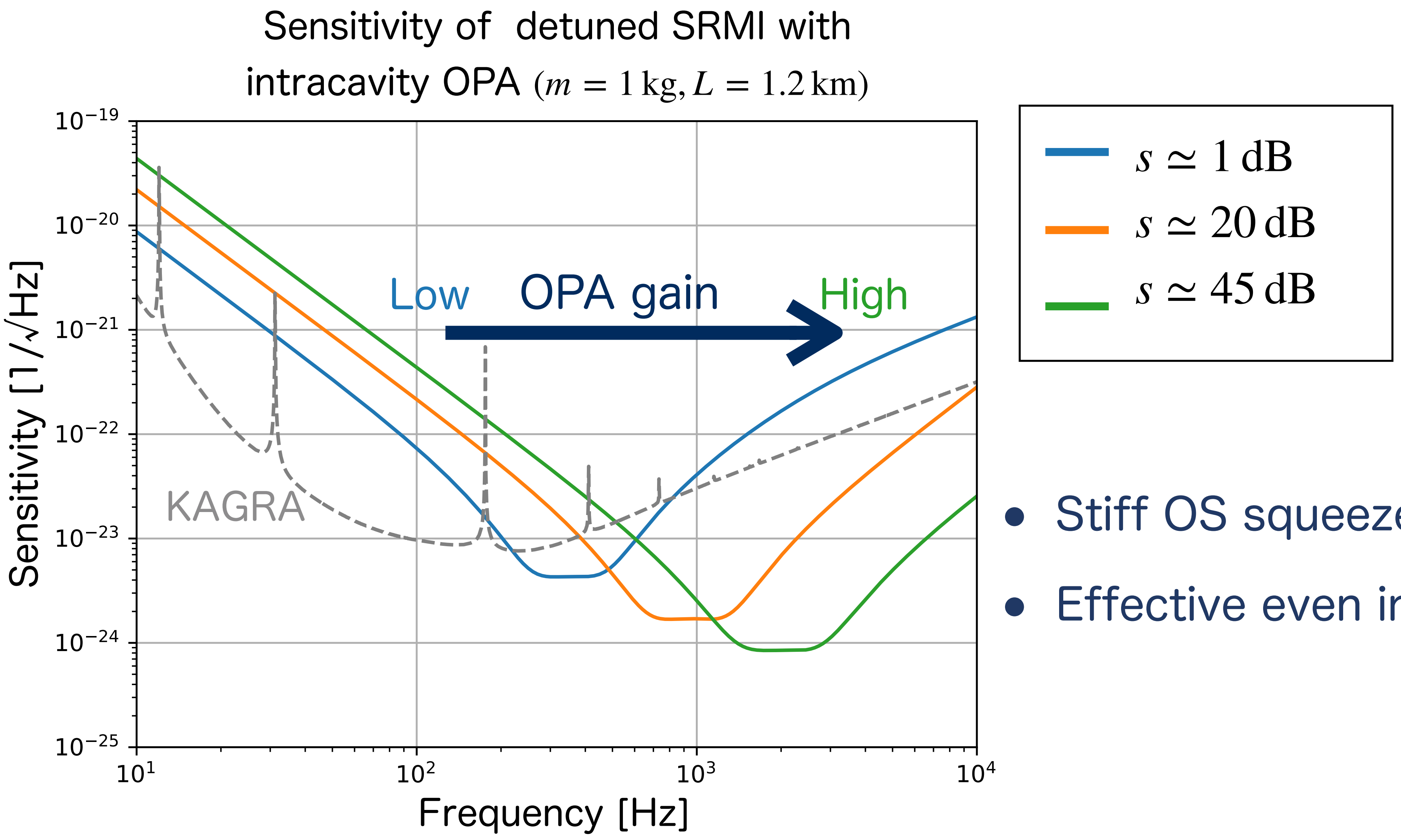


- OPA in SRC does not change the intracavity power but amplifies the signal and modifies the dynamics

  ➡ OPA-ed OS improves high frequency sensitivity

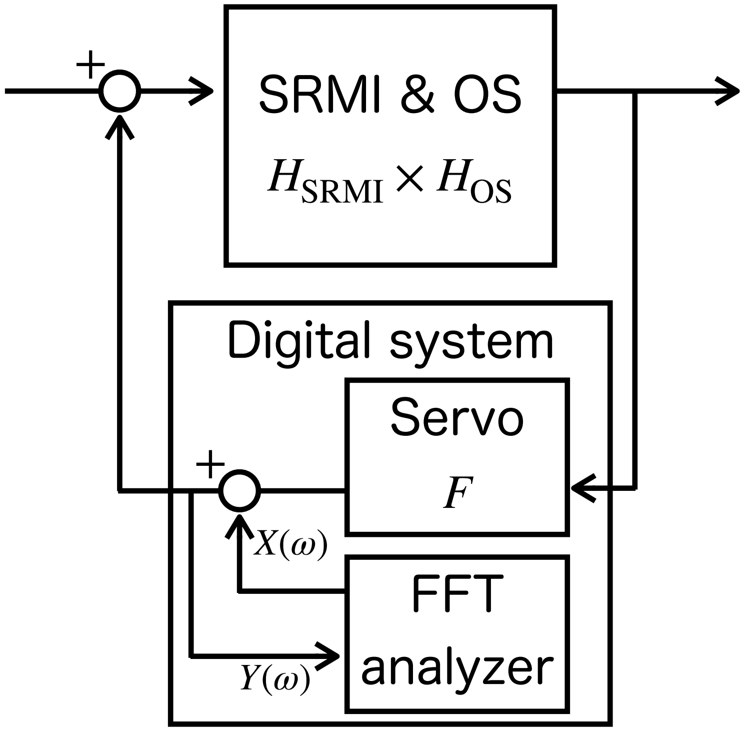


Sensitivity estimation

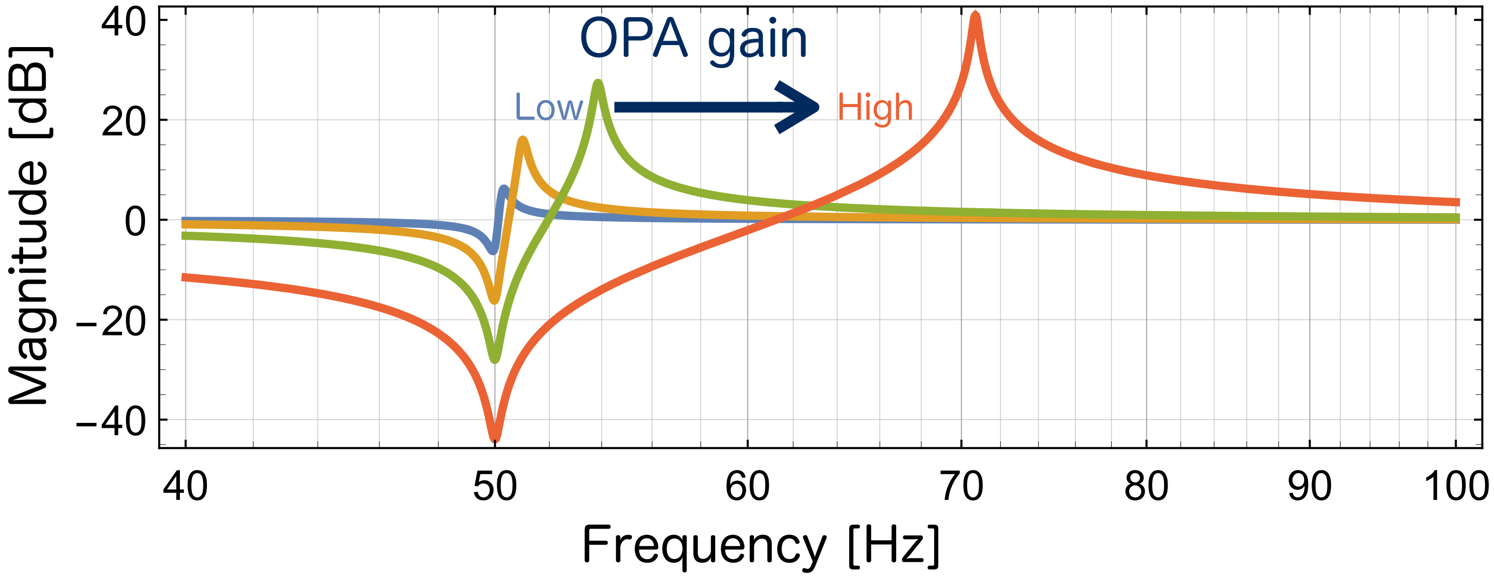


- Stiff OS squeezes the noise ellipse
- Effective even in lossy situation

Verification in transfer function

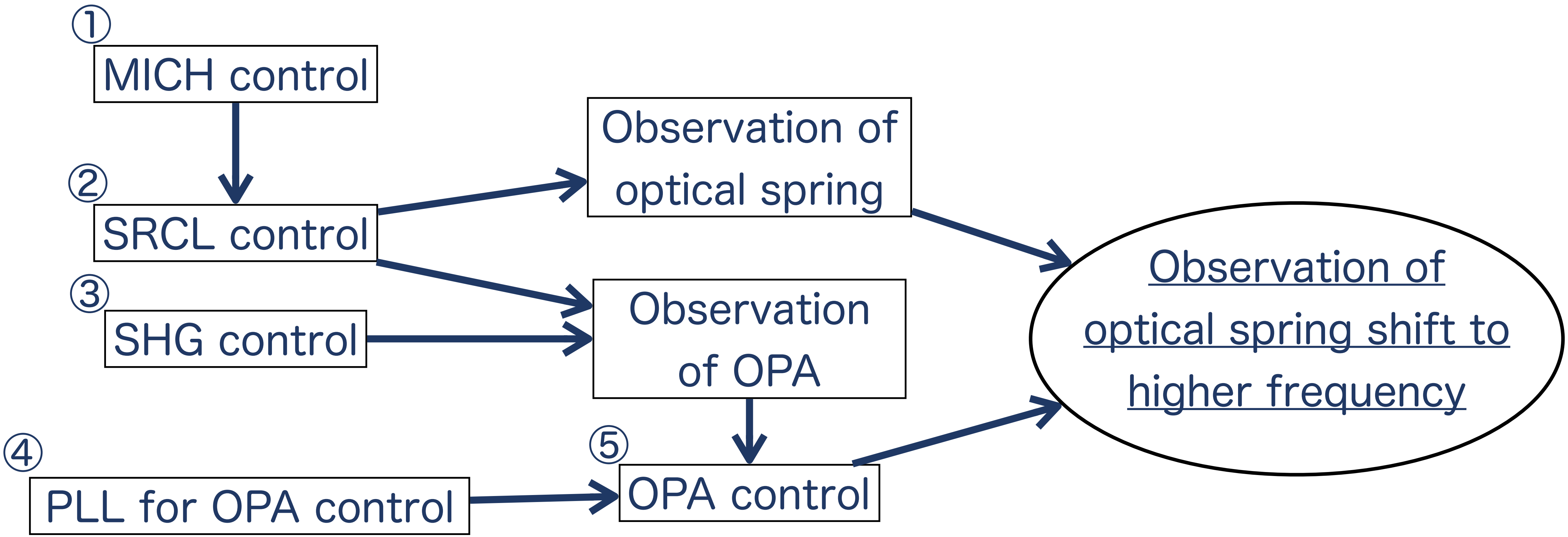


Transfer function of OS $H_{\mathrm{OS}}(\omega) \simeq \dfrac{\omega_{\mathrm{m}}^2 - \omega^2}{\omega_{\mathrm{m}}^2 + \omega_{\mathrm{OS}}^2 - \omega^2}$



Observe the optical spring f_{OS} shift to higher frequency

Experimental flowchart

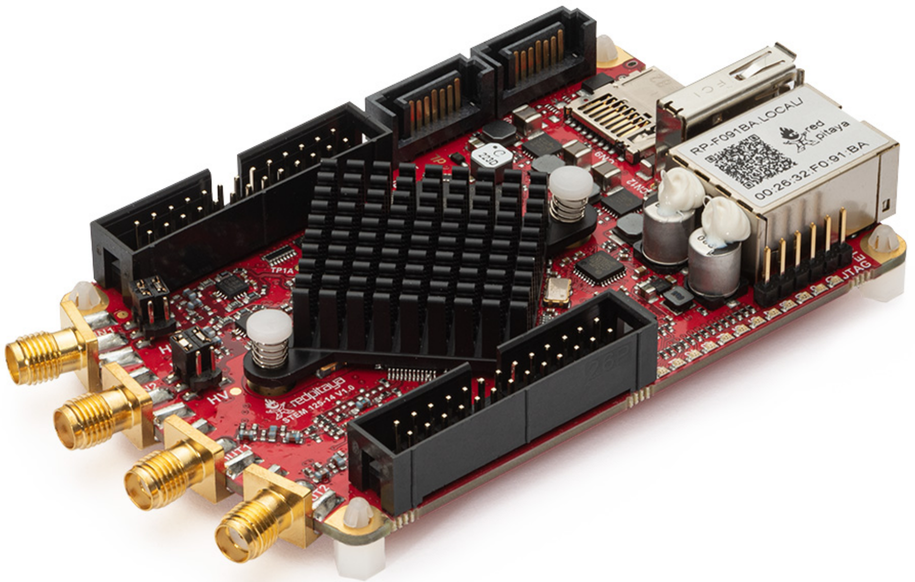


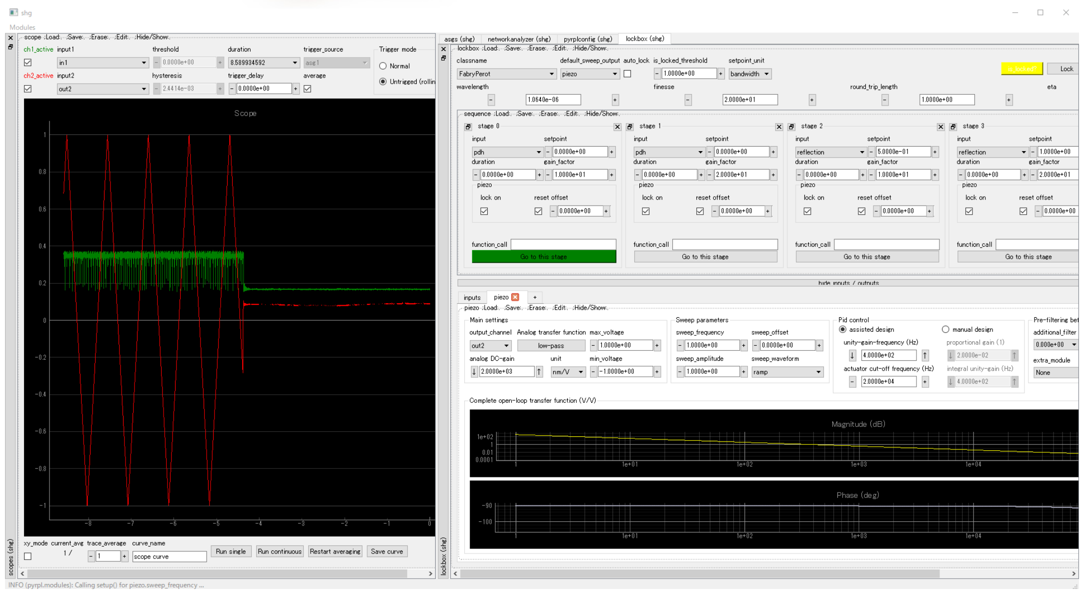
MICH: Michelson arm length
SRCL: Signal recycling cavity length
SHG: Second harmonic generation
PLL: Phase-locked loop

➡We need at least 5 DOFs control

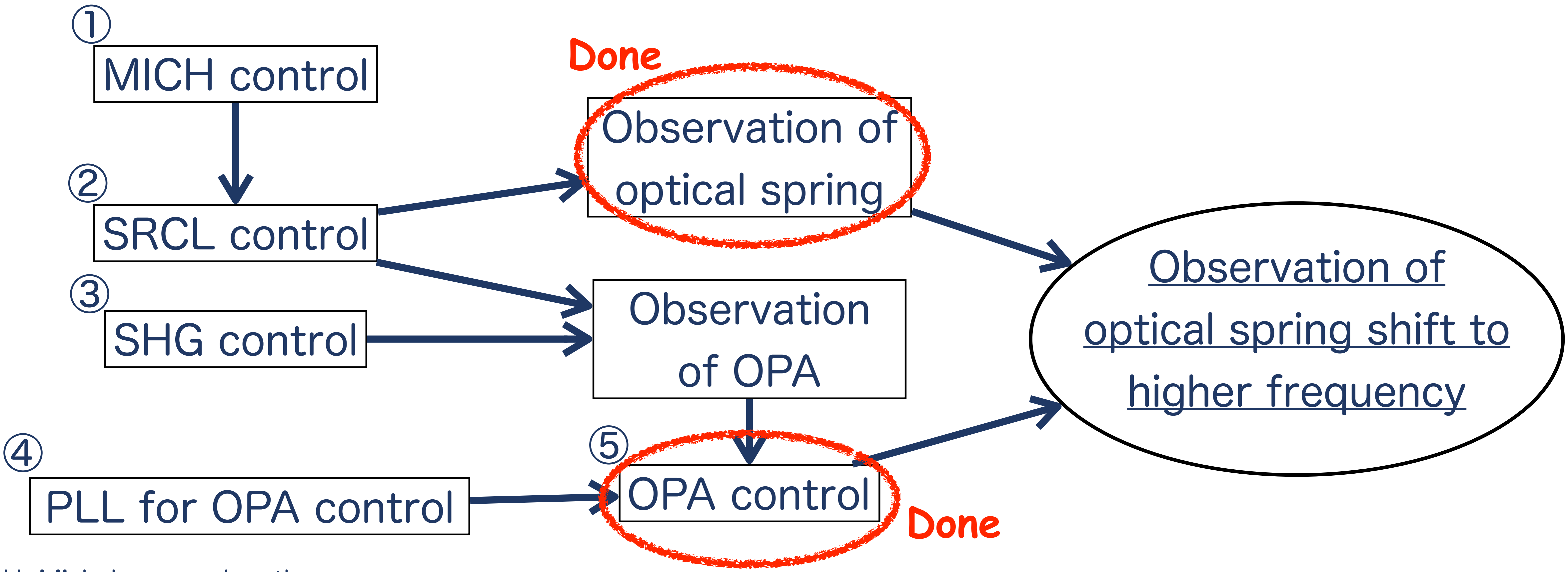
Digital control

- STEMlab 125-14 by redpitaya
  - 125 MS/s
  - 14 bit ADC/DAC
  - ~500 €
  - Run by Python code
- PyRPL(Python Red Pitaya Lockbox)
  - Free software for optical system control developed at Laboratoire Kastler Brossel — Physique quantique et applications



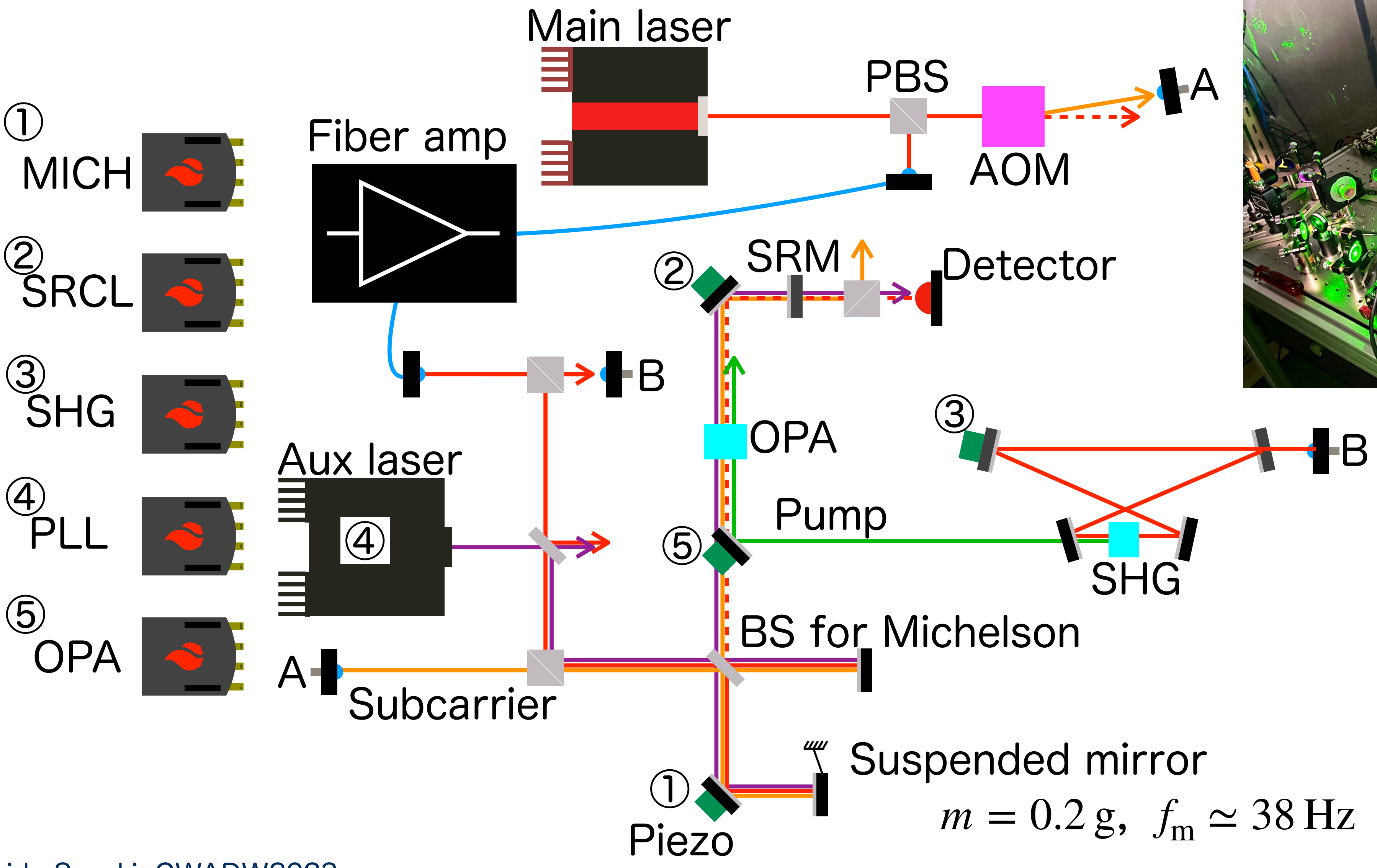


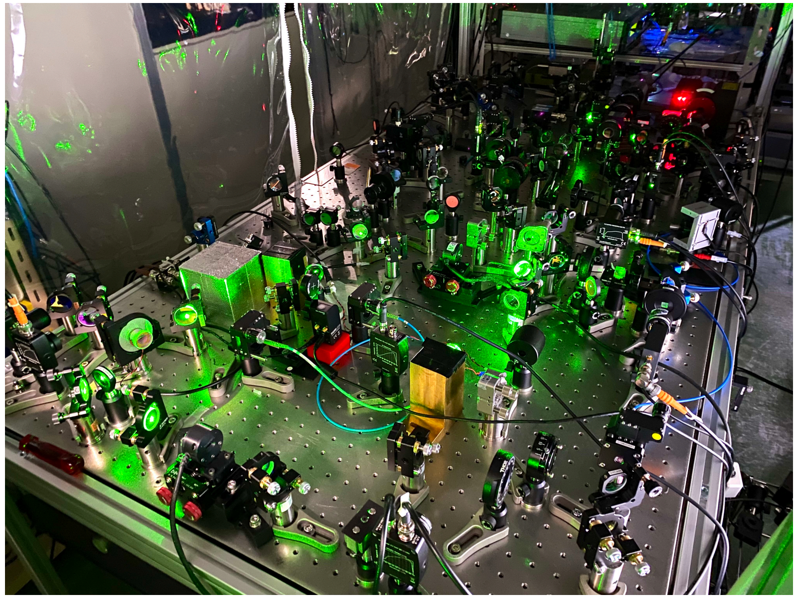
Experimental flowchart

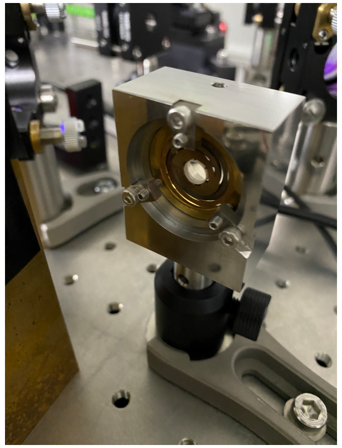


MICH: Michelson arm length
SRCL: Signal recycling cavity length
SHG: Second harmonic generation
PLL: Phase-locked loop

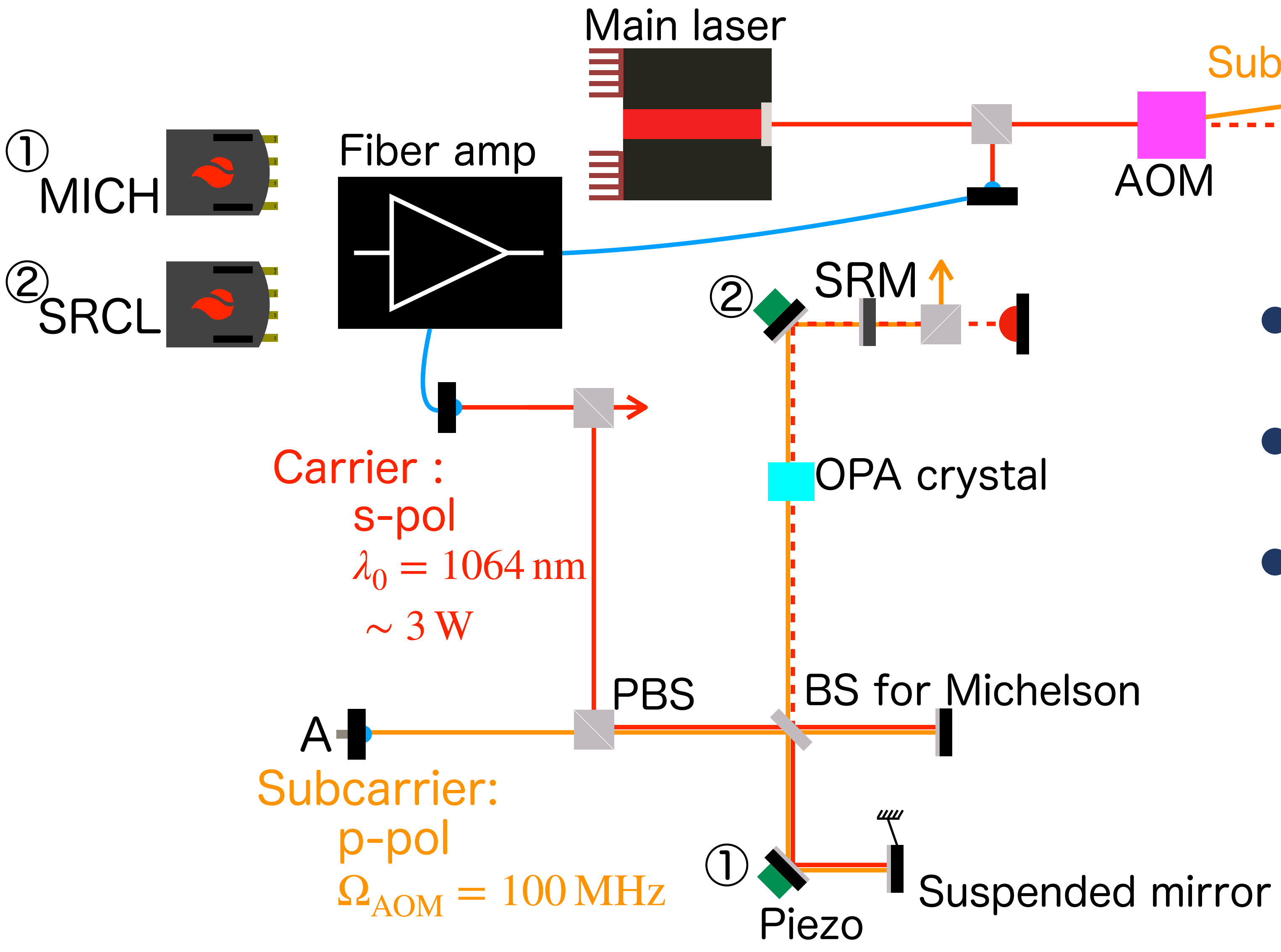
Experimental setup





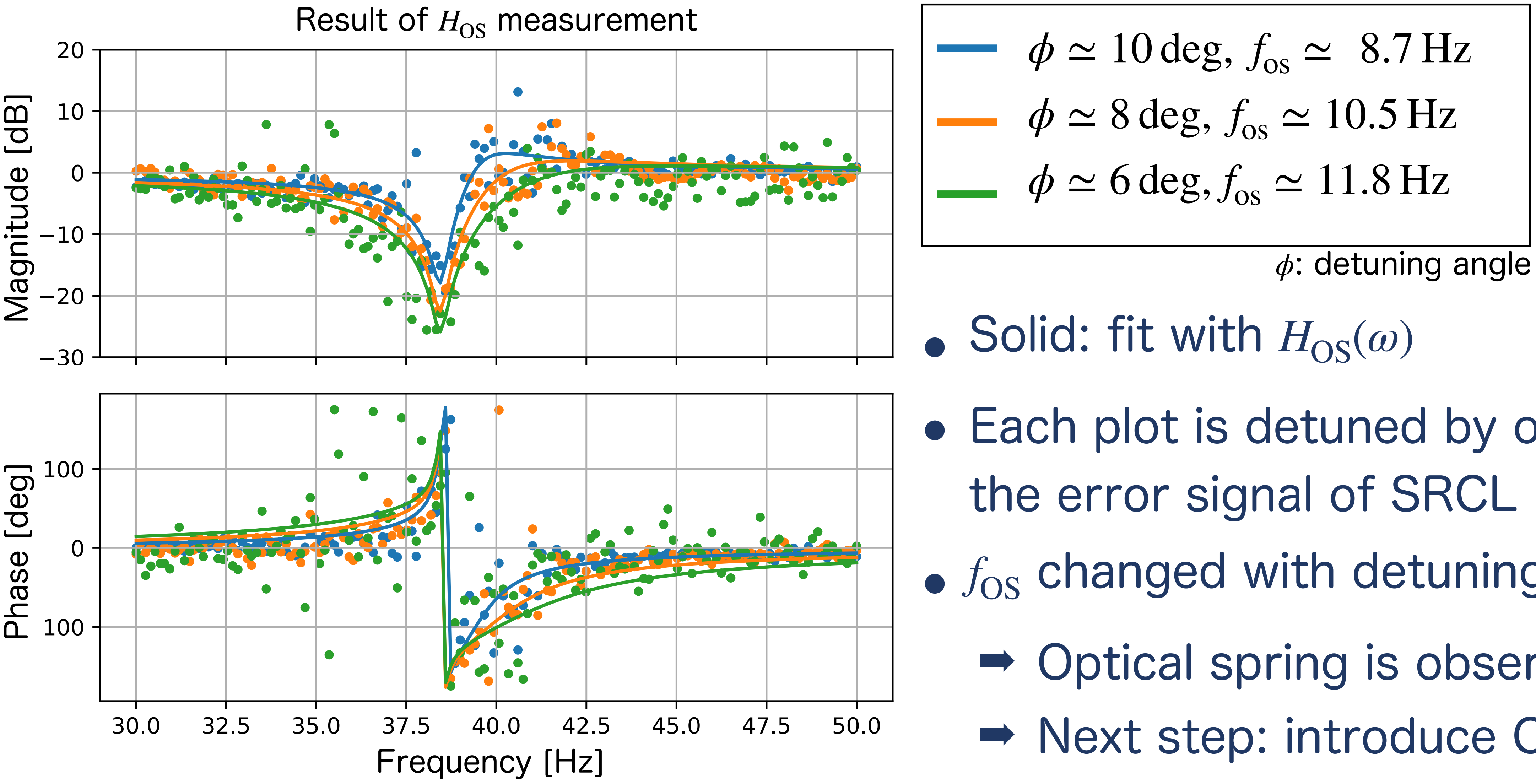


Observation of optical spring (without OPA)



- MICH: Dark
- SRCL: Resonance
- Carrier: 3W

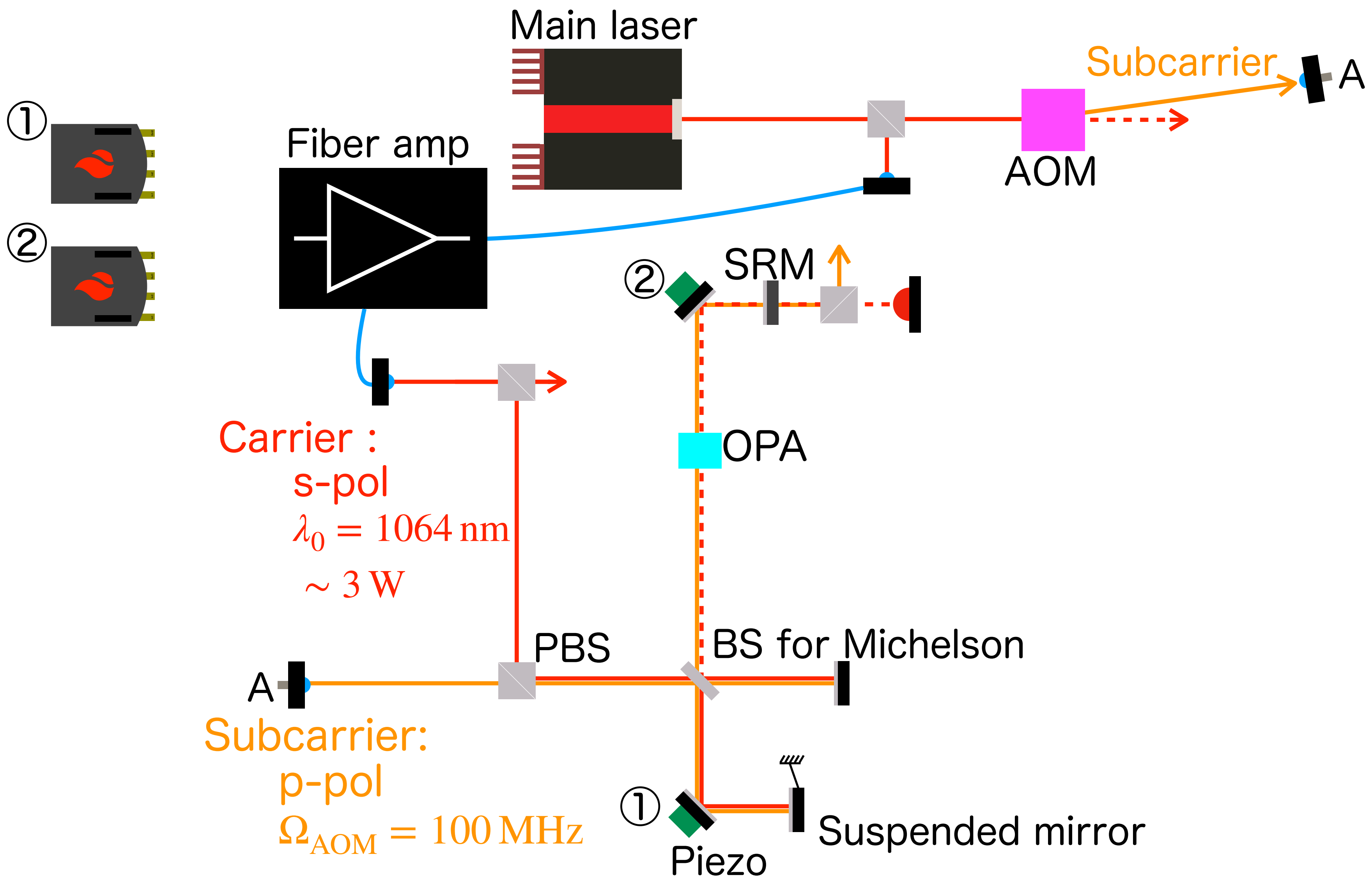
Observation of optical spring (without OPA)



ϕ: detuning angle

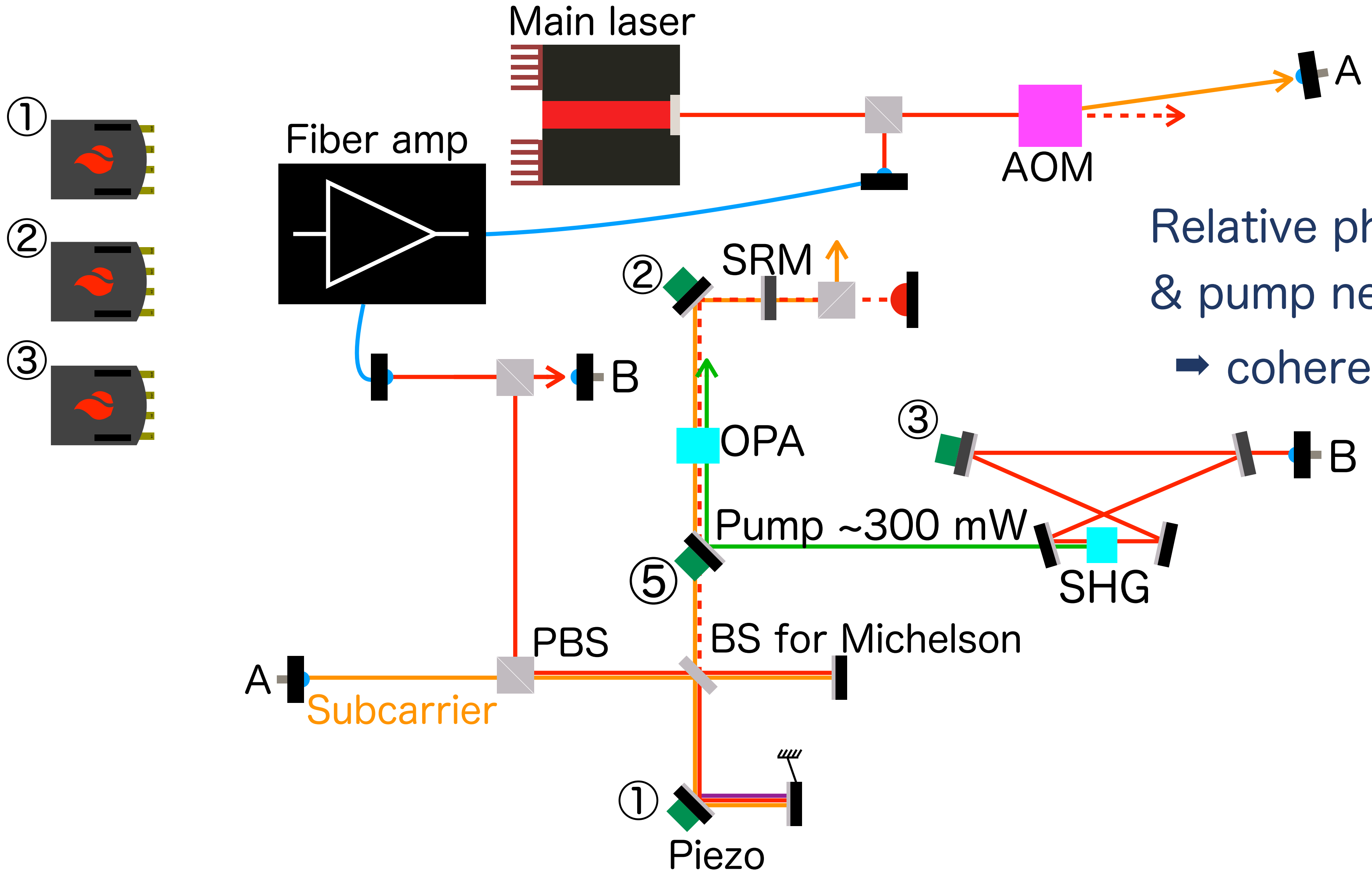
- Solid: fit with $H_{OS}(\omega)$
- Each plot is detuned by offsetting the error signal of SRCL
- f_{OS} changed with detuning
  - ➡ Optical spring is observed
  - ➡ Next step: introduce OPA

OPA control



①
②
Main laser
Fiber amp
Subcarrier
A
AOM
②
SRM
OPA
Carrier :
s-pol
$\lambda_0 = 1064\,\mathrm{nm}$
$\sim 3\,\mathrm{W}$
PBS
BS for Michelson
A
Subcarrier:
p-pol
$\Omega_{\mathrm{AOM}} = 100\,\mathrm{MHz}$
①
Piezo
Suspended mirror

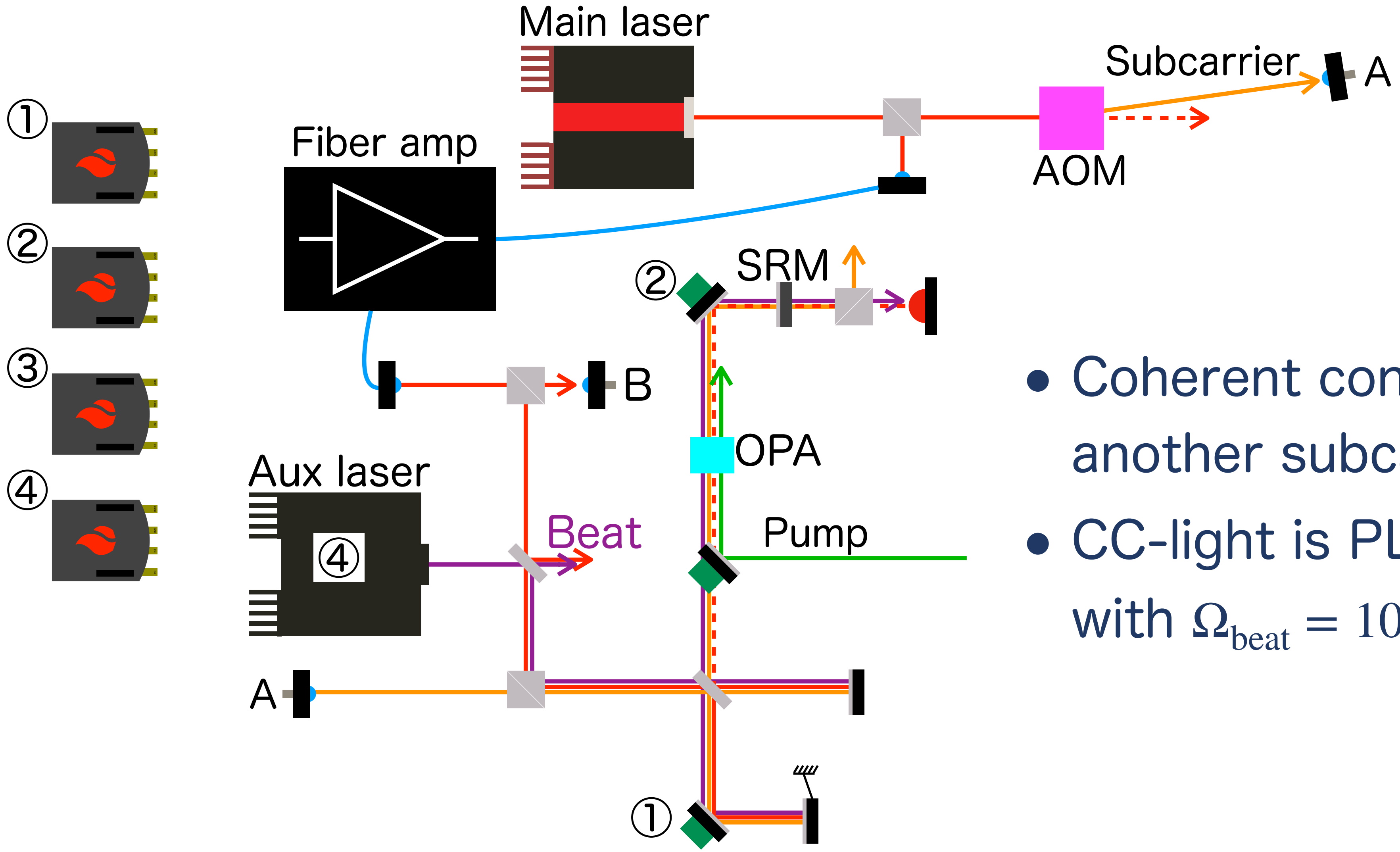
OPA control



Relative phase between carrier & pump needs to be controlled

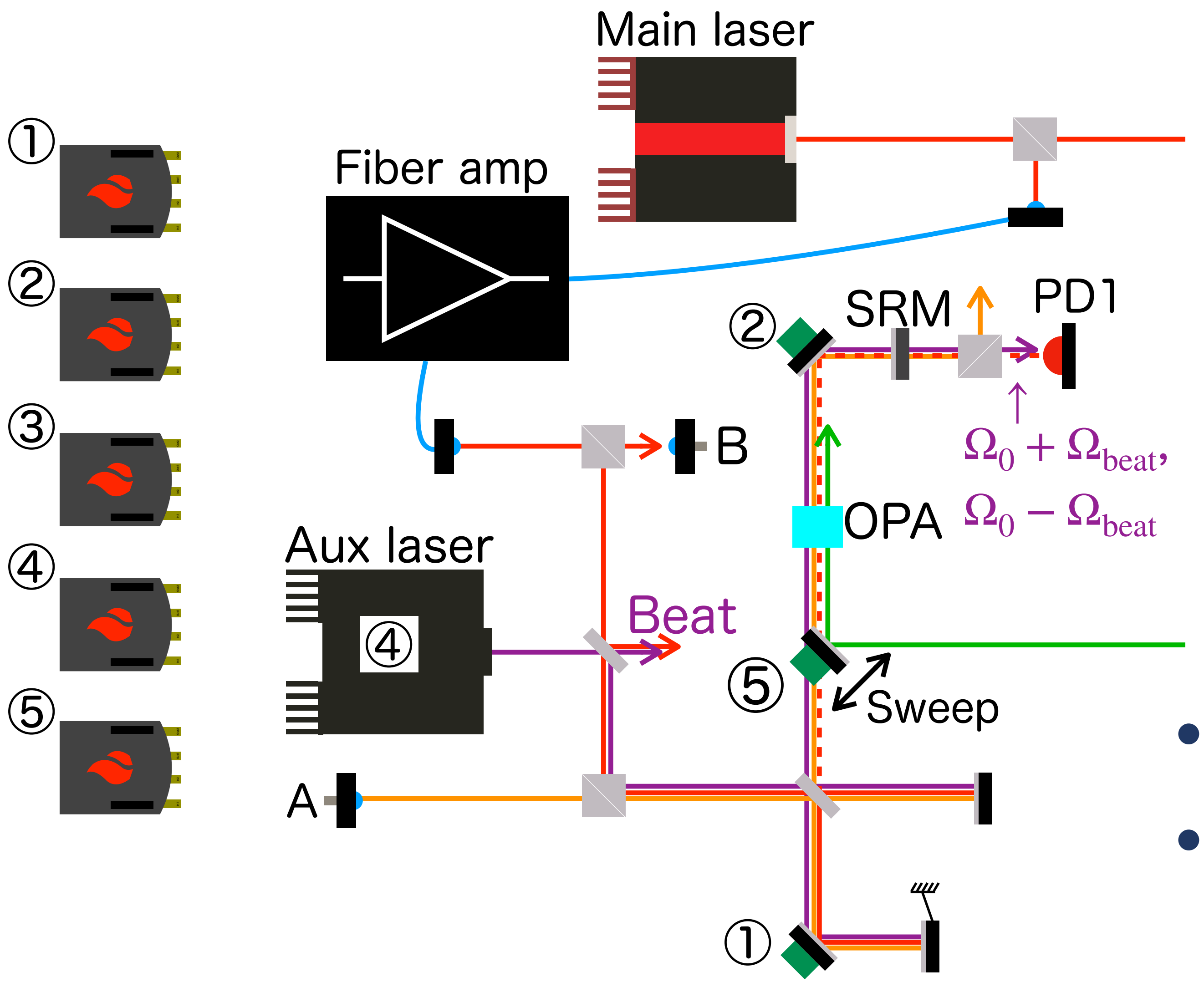
➡ coherent control technique

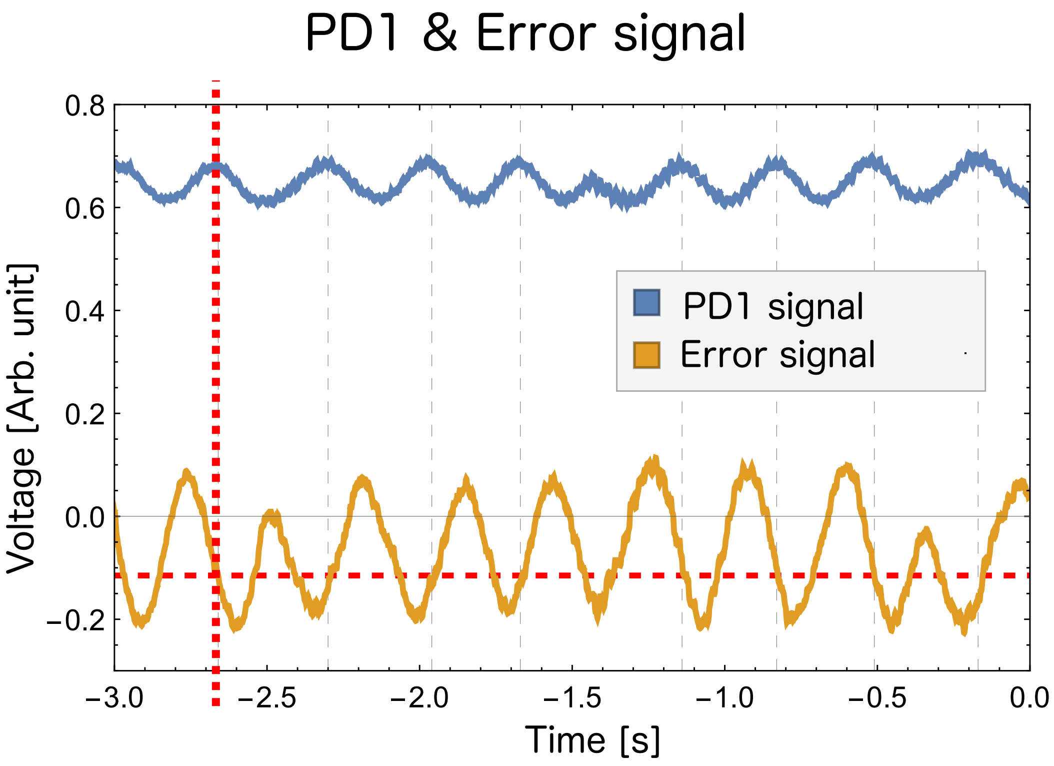
OPA control



- Coherent control of OPA requires another subcarrier (CC-light)
- CC-light is PLL-ed to the carrier with $\Omega_{\mathrm{beat}} = 10\,\mathrm{MHz}$ offset

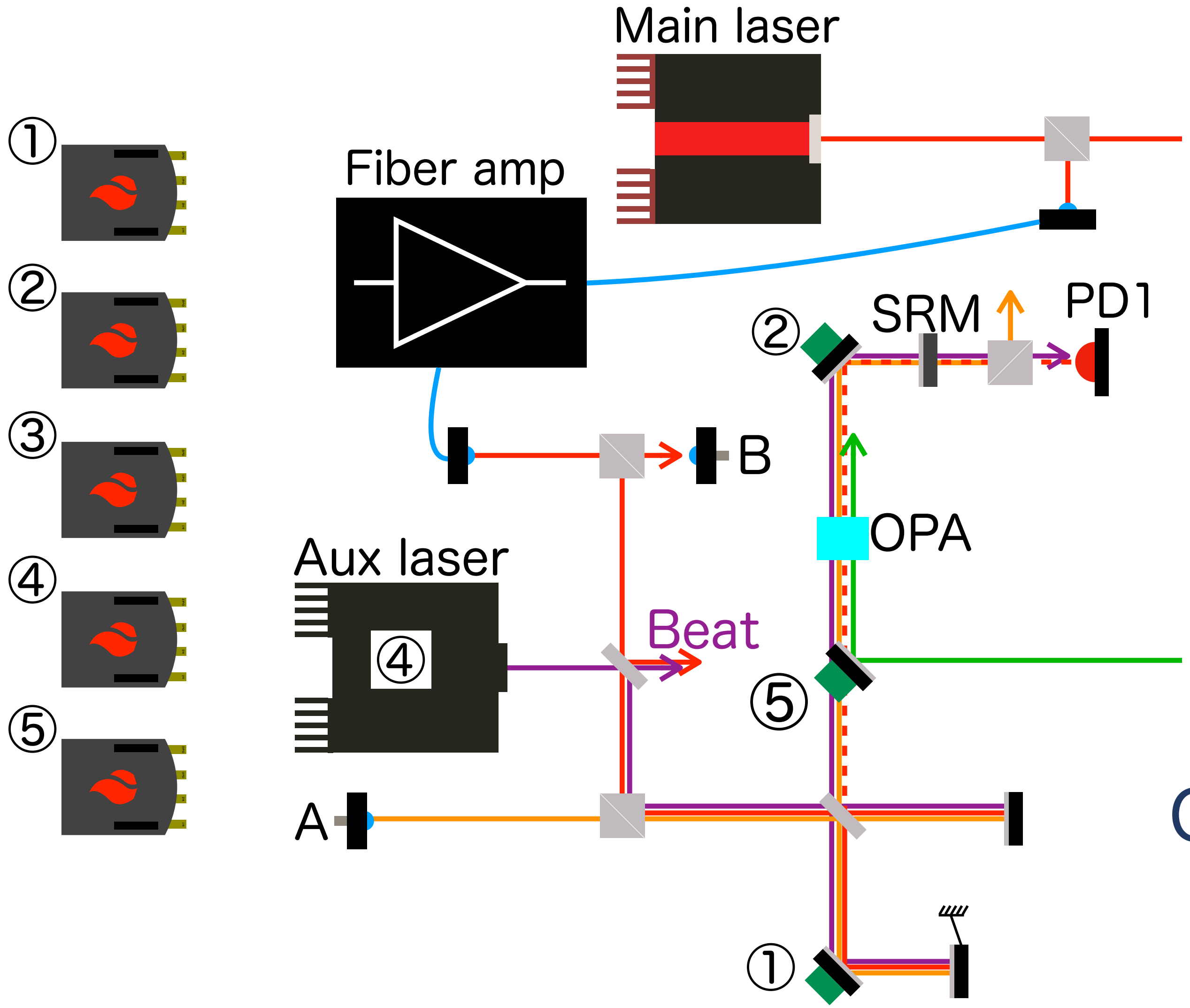
OPA control

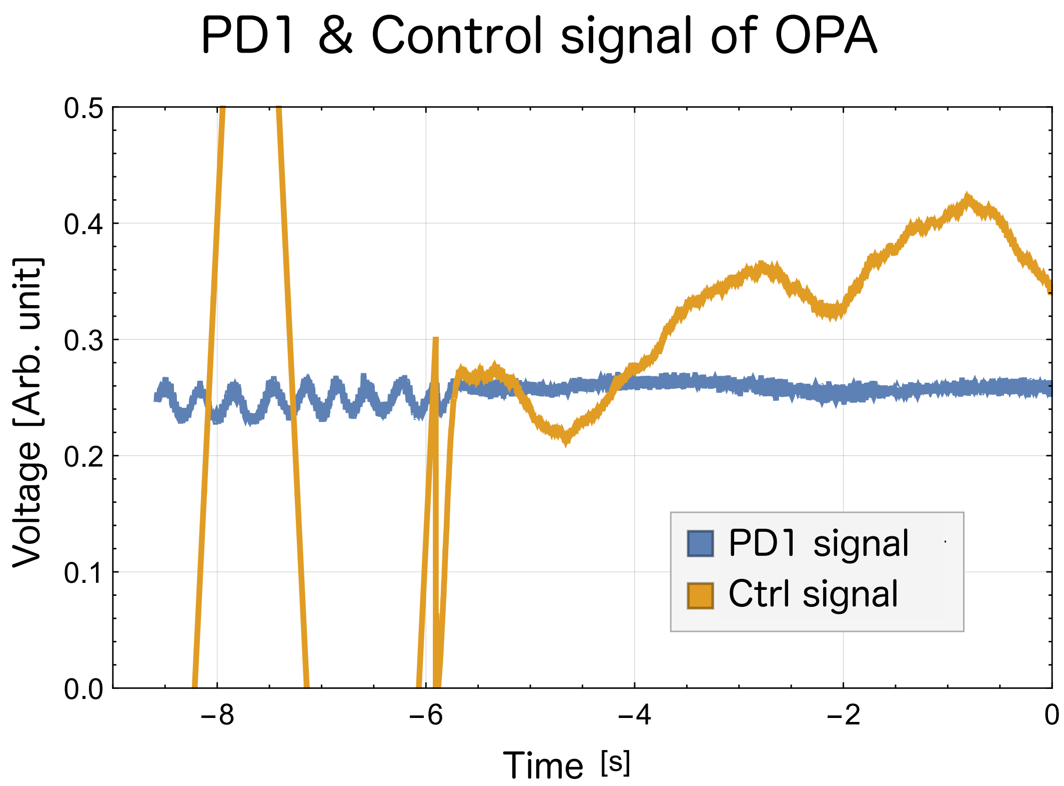




- Idler at $\Omega_0 - \Omega_{beat}$ is generated at OPA
- Demodulation at $2\Omega_{beat} = 20\,\mathrm{MHz}$ gives an error signal

OPA control





OPA was successfully locked

Status

- We have not succeeded in seeing the optical spring moves with OPA
- Since the frequency shift may be small, we are trying to stabilize the interferometer control
    - Reduce vibration from laser amps
    - Improve intensity stability of pump

Summary

- OPA in SR cavity enables stiff optical spring
- We have observed optical spring in SRMI
- Simultaneous control of 5 DOFs including coherent control of OPA was realized by digital system

Next work

- Verify the enhance of optical spring by measuring transfer functions with different OPA gains

Tokyo Tech

Development of a signal amplification technique using nonlinear optical effects for next-generation gravitational wave detectors

Kaido Suzuki, Ken-ichi Harada, Sotatsu Otabe, Kentaro Somiya

Tokyo Institute of Technology

2023-5-26 (Fri)