Development of a Control Scheme of Signal Recycling Interferometer with the Nonlinear Optical Effect

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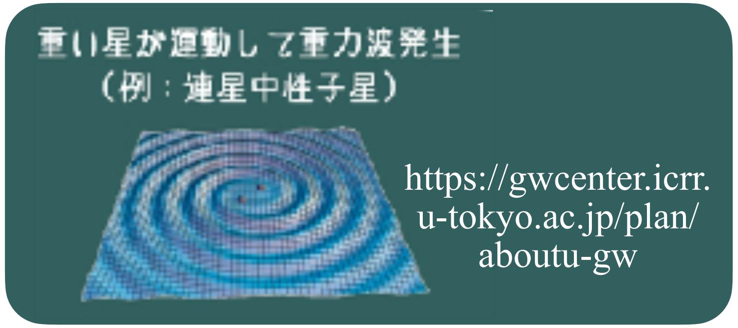
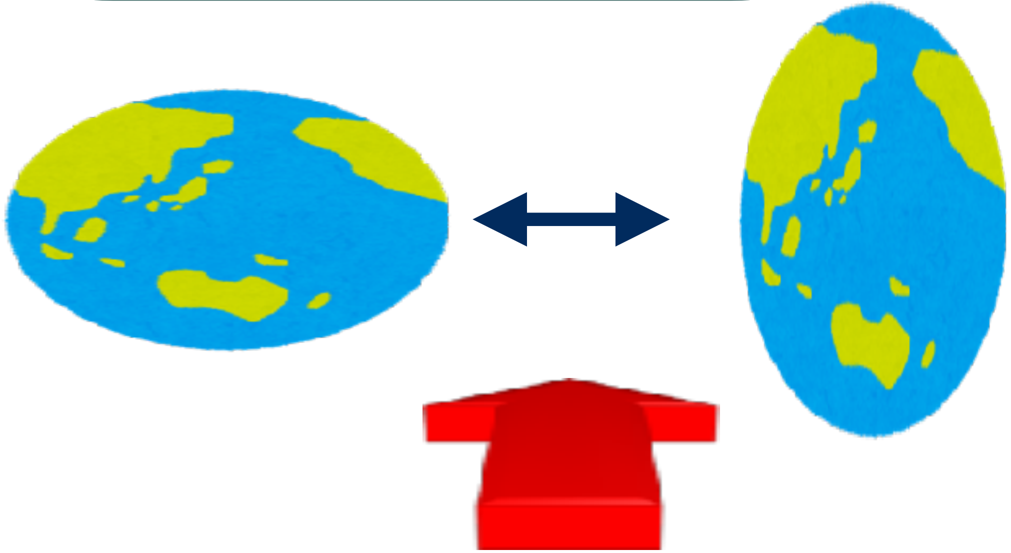
What are Gravitational Waves?

- Ripples in spacetime, caused by accelerated masses
- Propagate at the speed of light



- Plane vertical to the direction of propagation is stretched or squeezed in differential ways

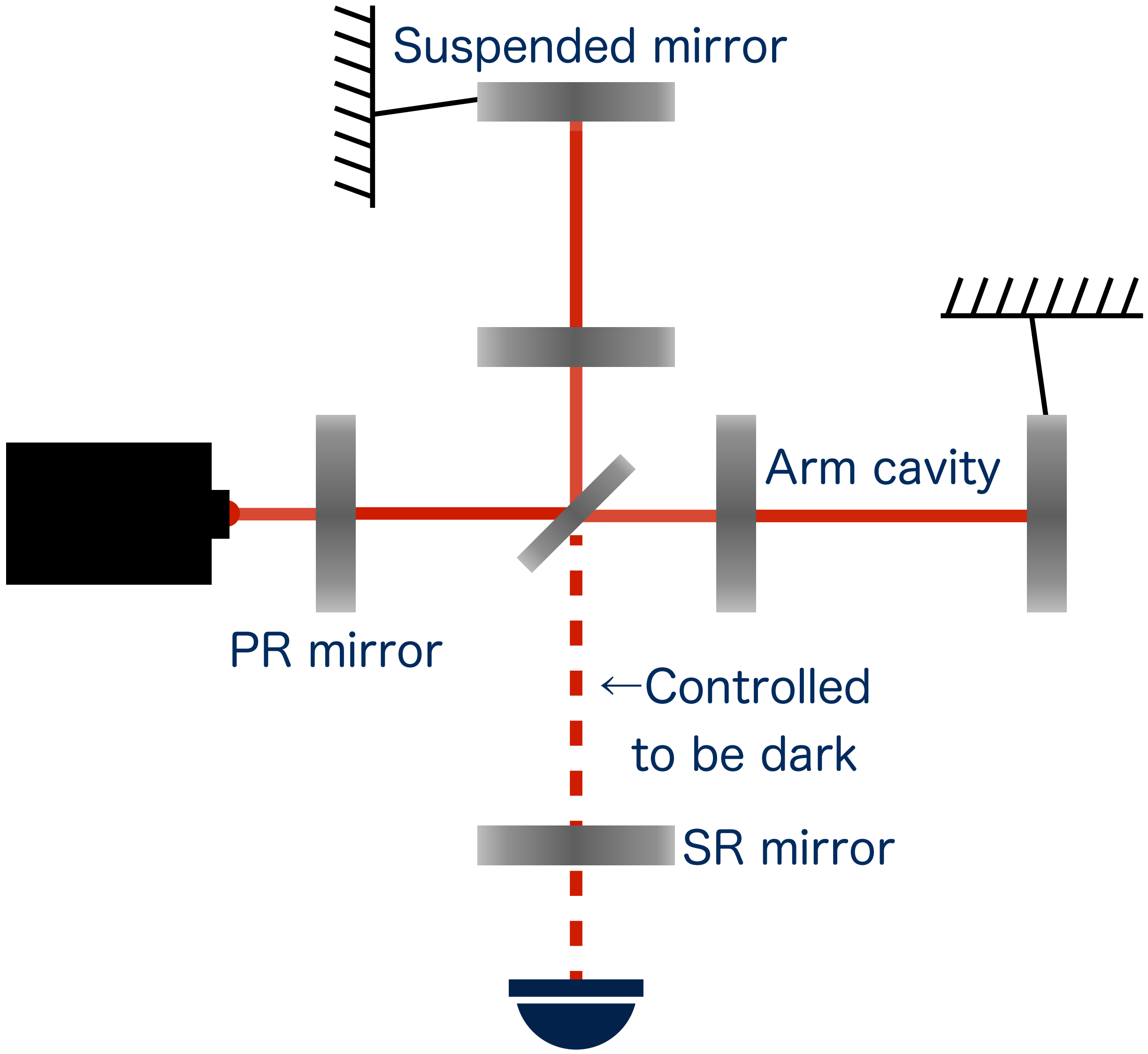
➡ Detected with a Michelson interferometer (MI)



Gravitational wave detector

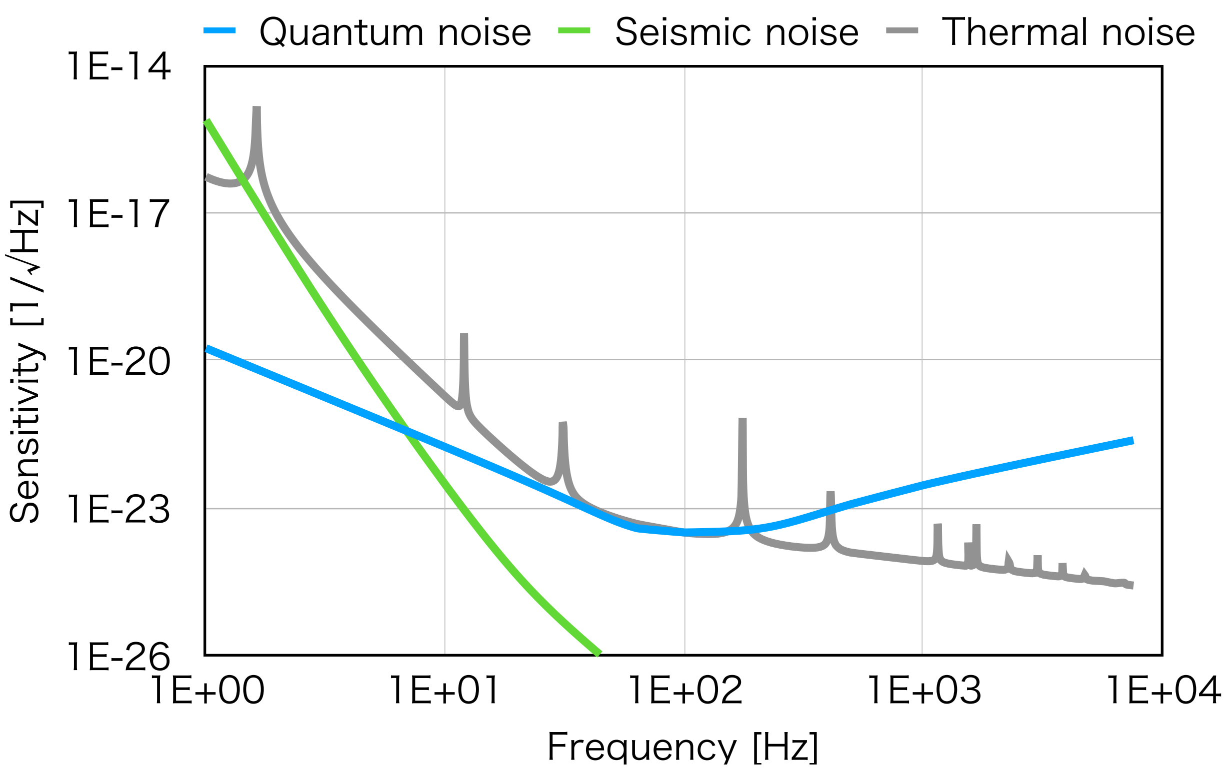
- Current detectors
  - KAGRA🇯🇵, LIGO🇺🇸, Virgo🇮🇹, etc.
- Signal amplification systems
  - Arm cavities
  - Power recycling
  - Signal recycling

➡ Intracavity power is limited by technical issues



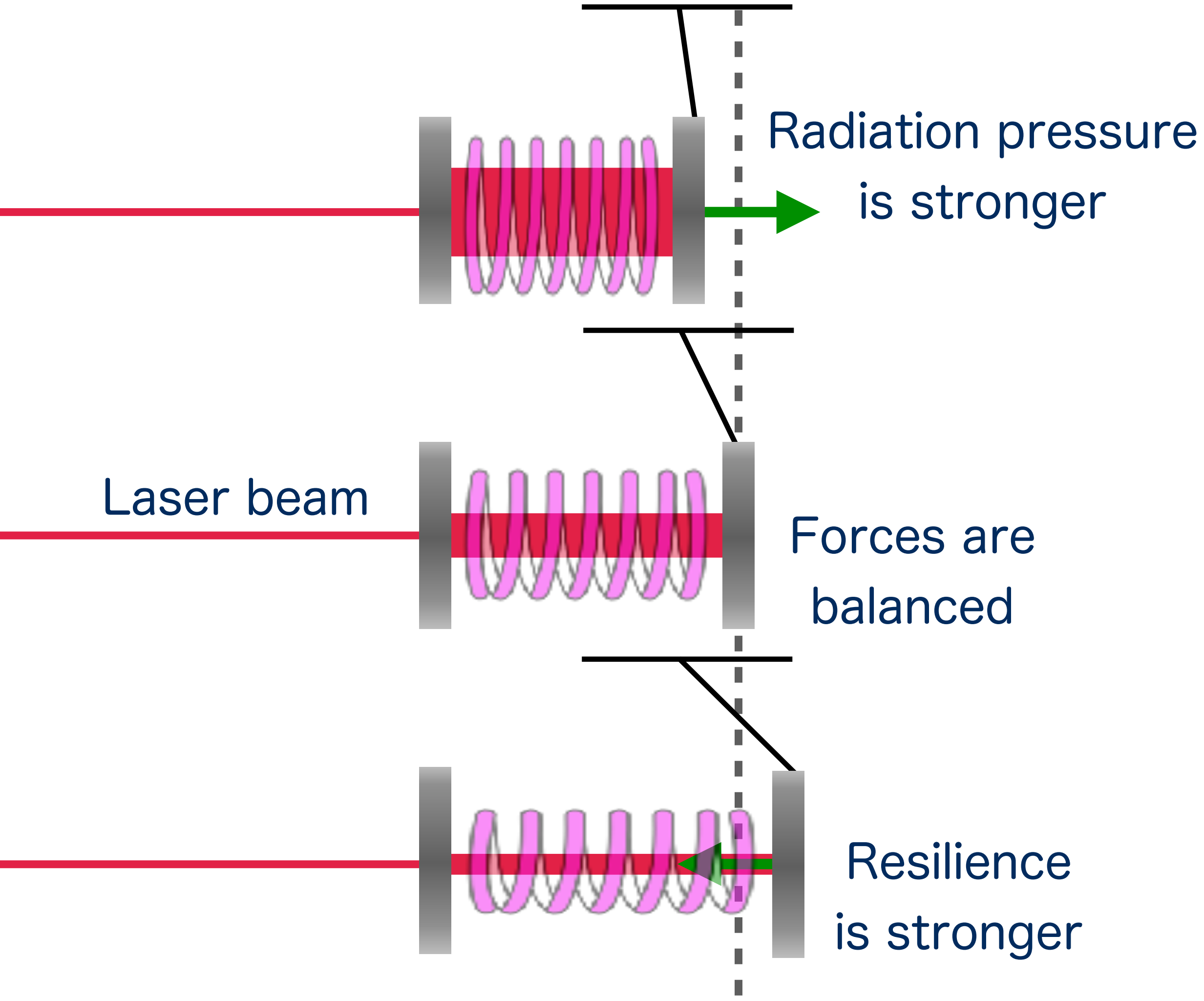
Previous Observations

- September, 2015: First detection
- 90 events were observed to date
  - ➡ High freqs are limited by shot noise
  - ➡ BNS post merger signal is yet to be clearly observed
- New method for high sensitivity
  - ➡ Optical spring



Noise in KAGRA

Optical spring (OS)



- “Spring” caused by interaction of optics and mechanics
- Generated by detuning the cavity from the resonant position
- GW signals are amplified at around the resonance frequency f_{OS}

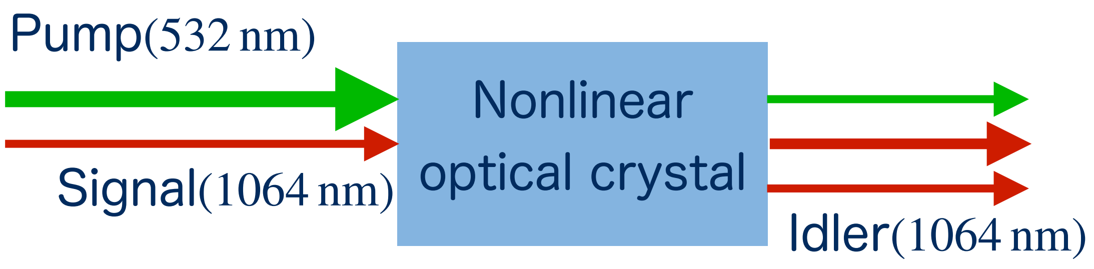
➡ $f_{\mathrm{OS}}^2 \propto$ Radiation pressure

$\propto$ laser power

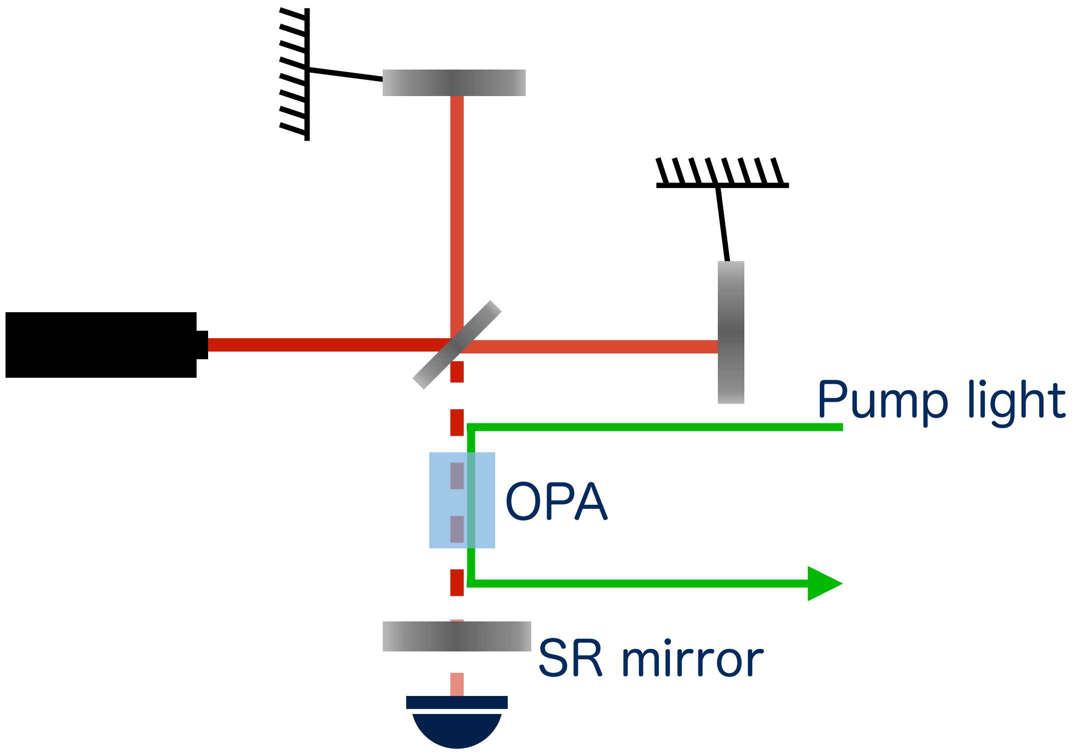
➡100’s of Hz is the current limit

Optical parametric amplification(OPA)

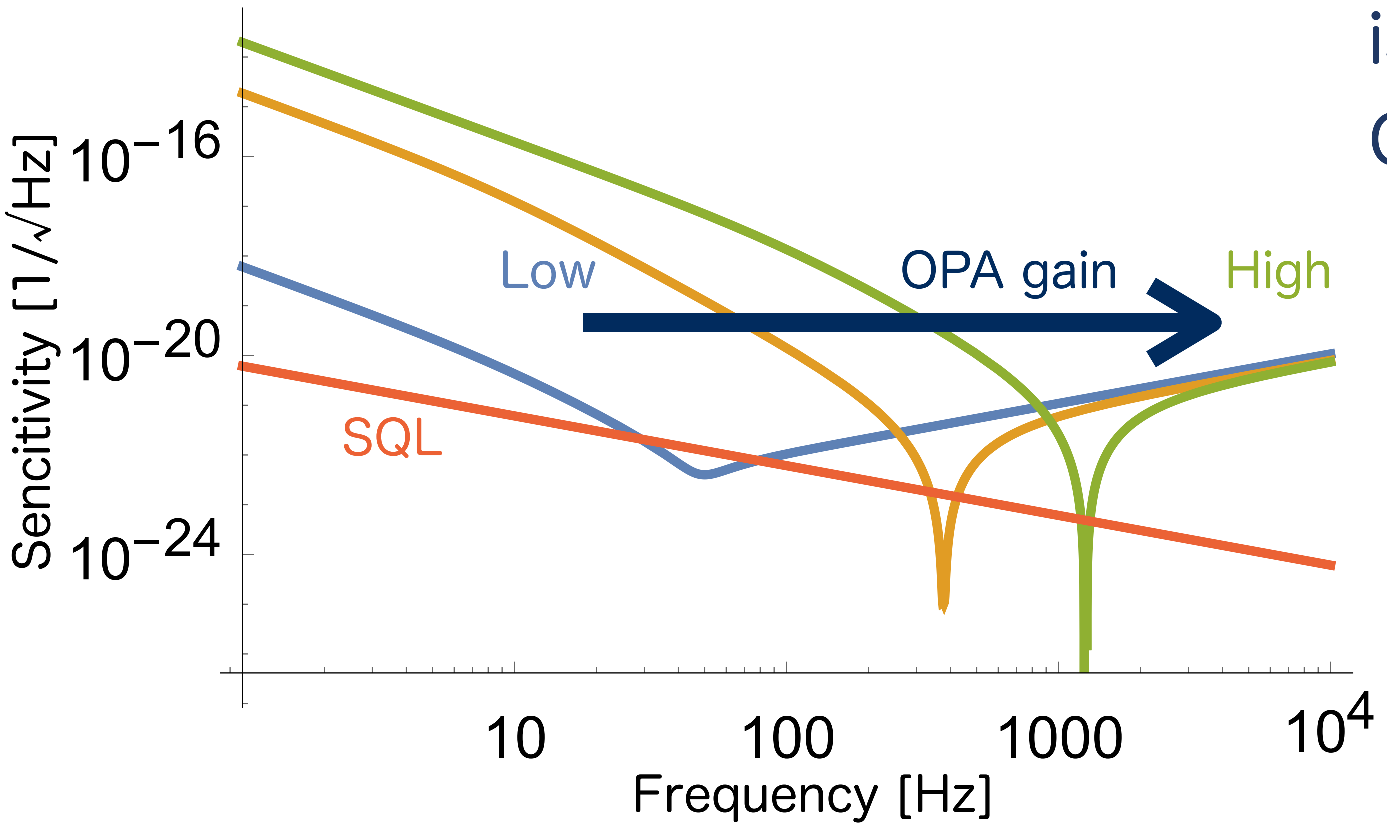
- The pump light is converted into signal and idler light by second-order nonlinear optical effects: $\omega_{\text{idler}} = \omega_{\text{pump}} - \omega_{\text{signal}}$



- OPA in SRMI
  - ➡ Stiff OS can be realized
  - ➡ Sensitivity at high freqs will be improved



Estimation of sensitivity



- Sensitivity at high frequencies is improved by increasing OPA gain

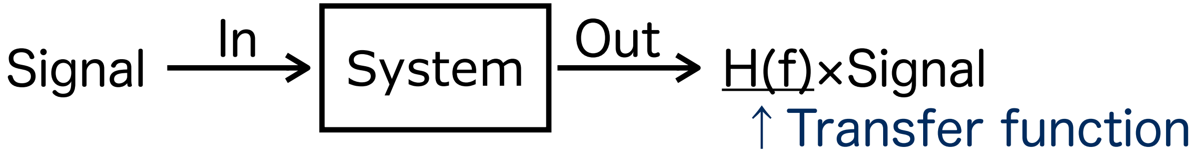
    ➡ Observation of events in the kHz band will be realized

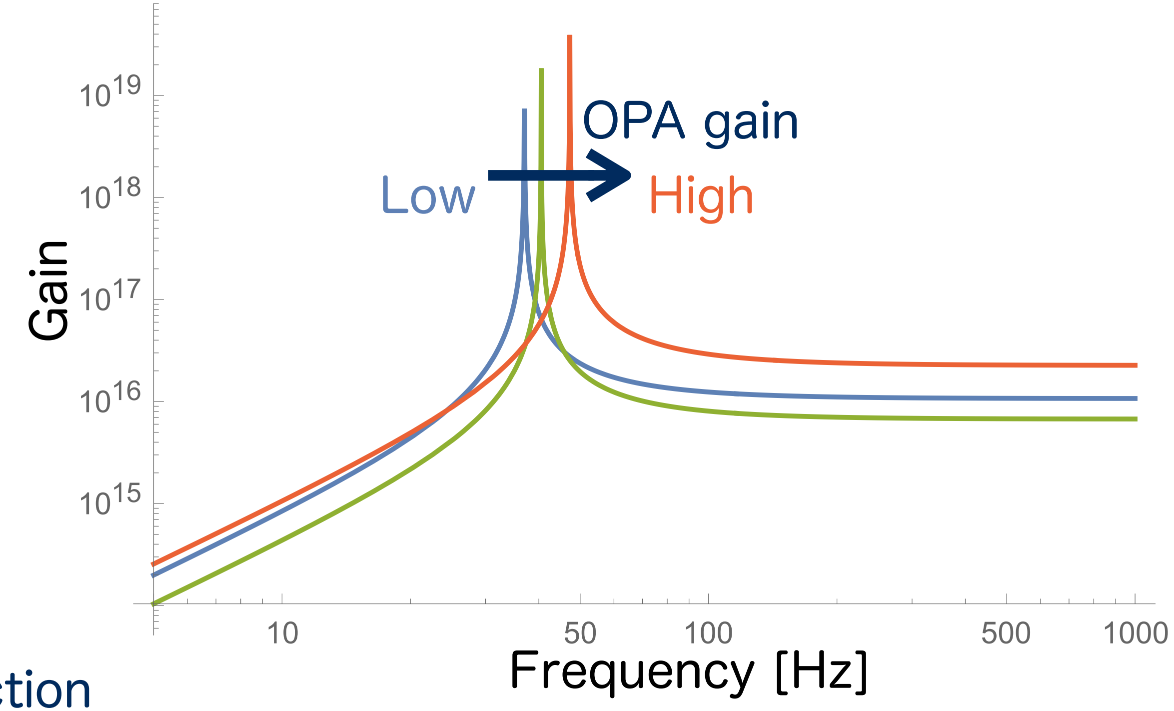
    - Binary neutron star mergers
    - Supernova

Method of the verification

Observe the changes in f_{OS} with increasing OPA gain on the transfer function

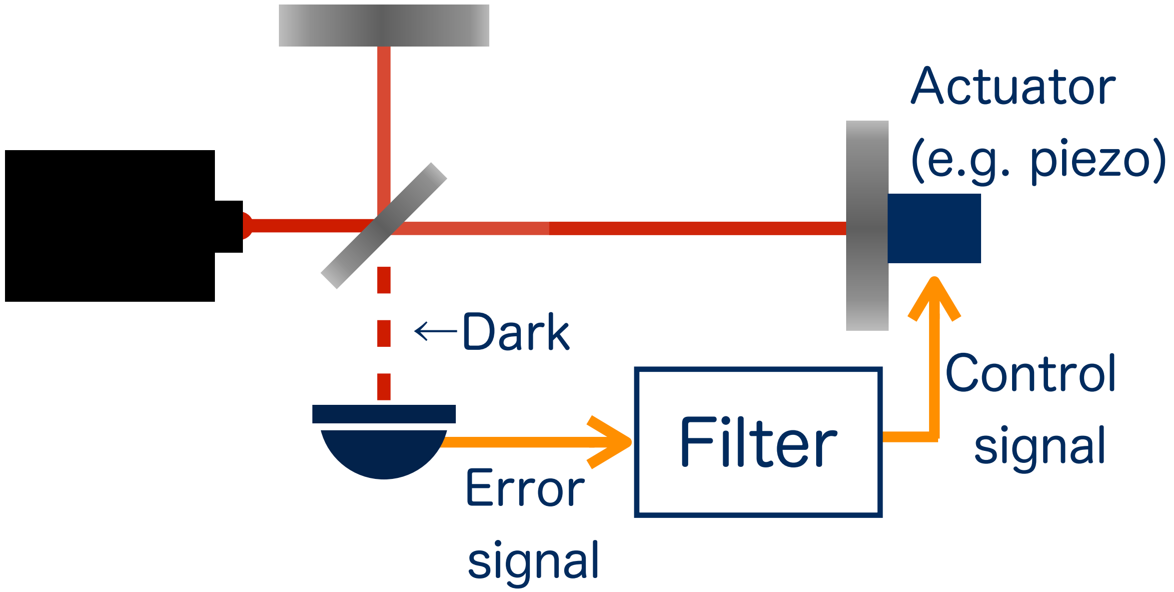
Transfer function:
- frequency response
- function representing the input-output relation of the system





Feedback control

- To observe the optical spring, the interferometer needs to be stably controlled



- Degrees of freedom to be controlled
  - MI differential length
  - SR cavity length
  - SHG cavity length
  - Pump intensity stabilization
  - Coherent control of OPA
  - PLL of CC light

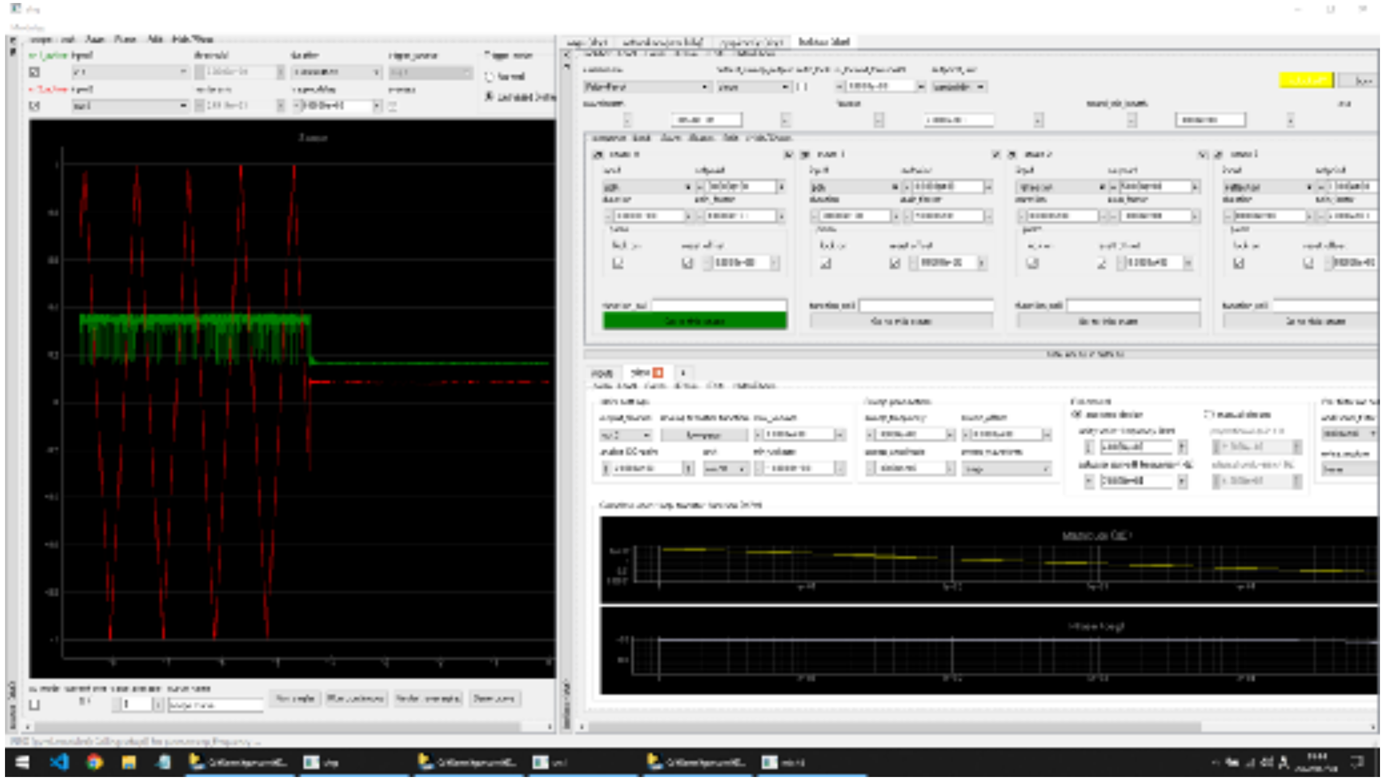
➡Digital control is preferred

Digital control

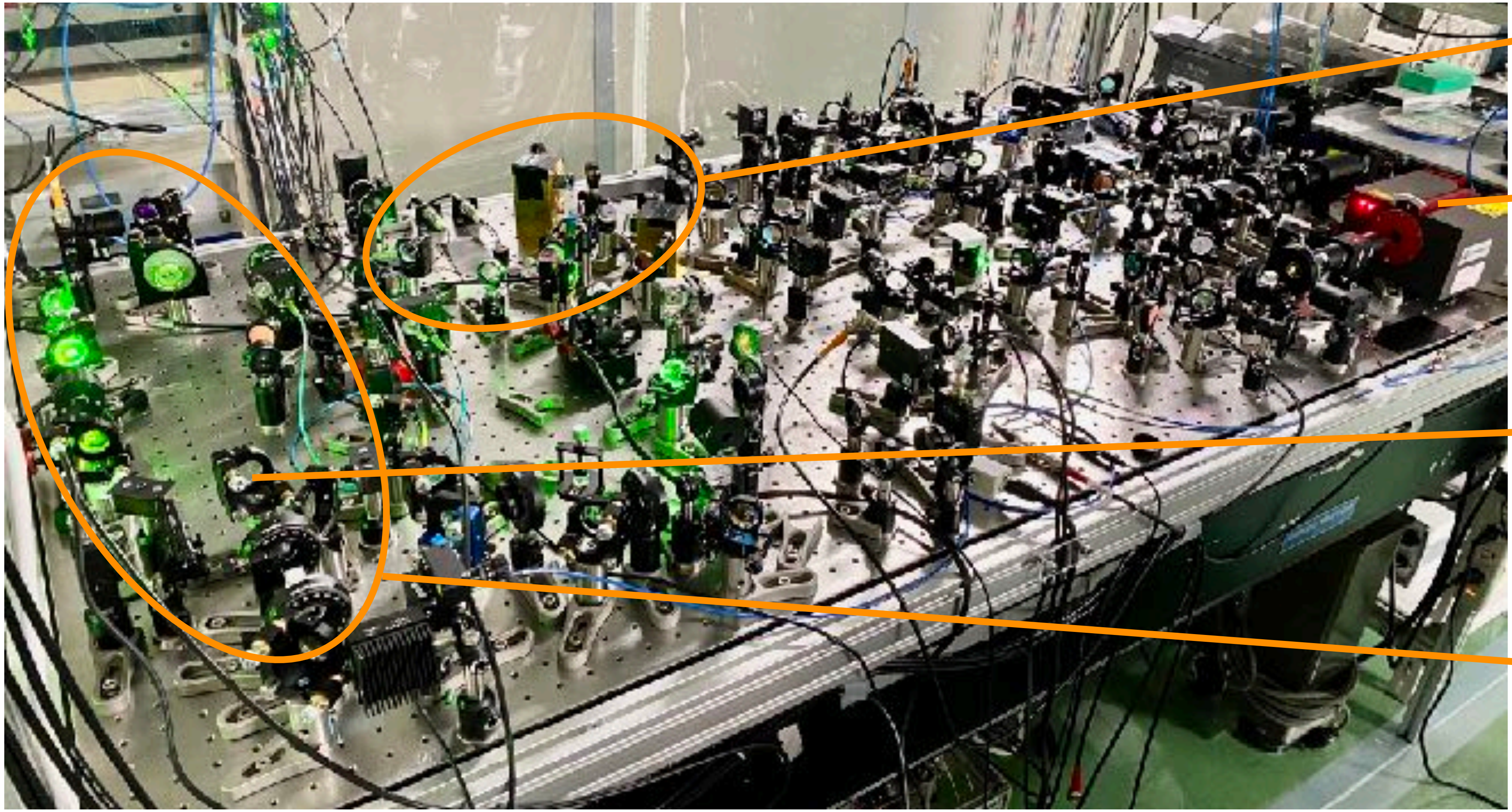
- STEMlab 125-14
  - Provided by redpitaya
  - 125 MS/s
  - 14 bit ADC/DAC
  - ~40 $
  - Run by Python code

Digital control

- PyRPL
  (Python Red Pitaya Lockbox)
  - Free software for optical system control developed at Lab. Kastler Brossel, our collaborator
  - The lockbox module can be used for control optical systems by PI control



Experimental set up



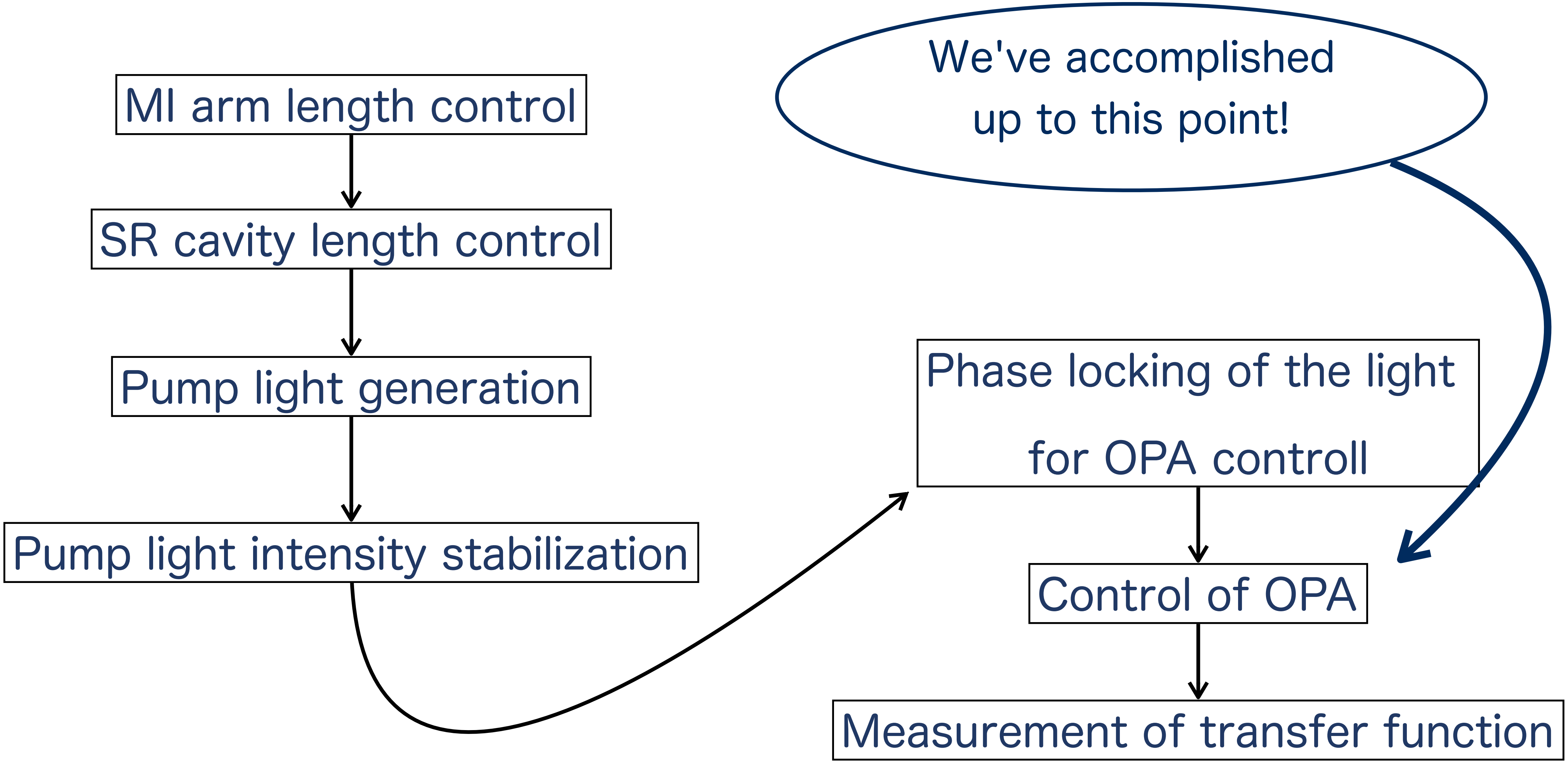
MI

Main laser
(1064 nm, IR)

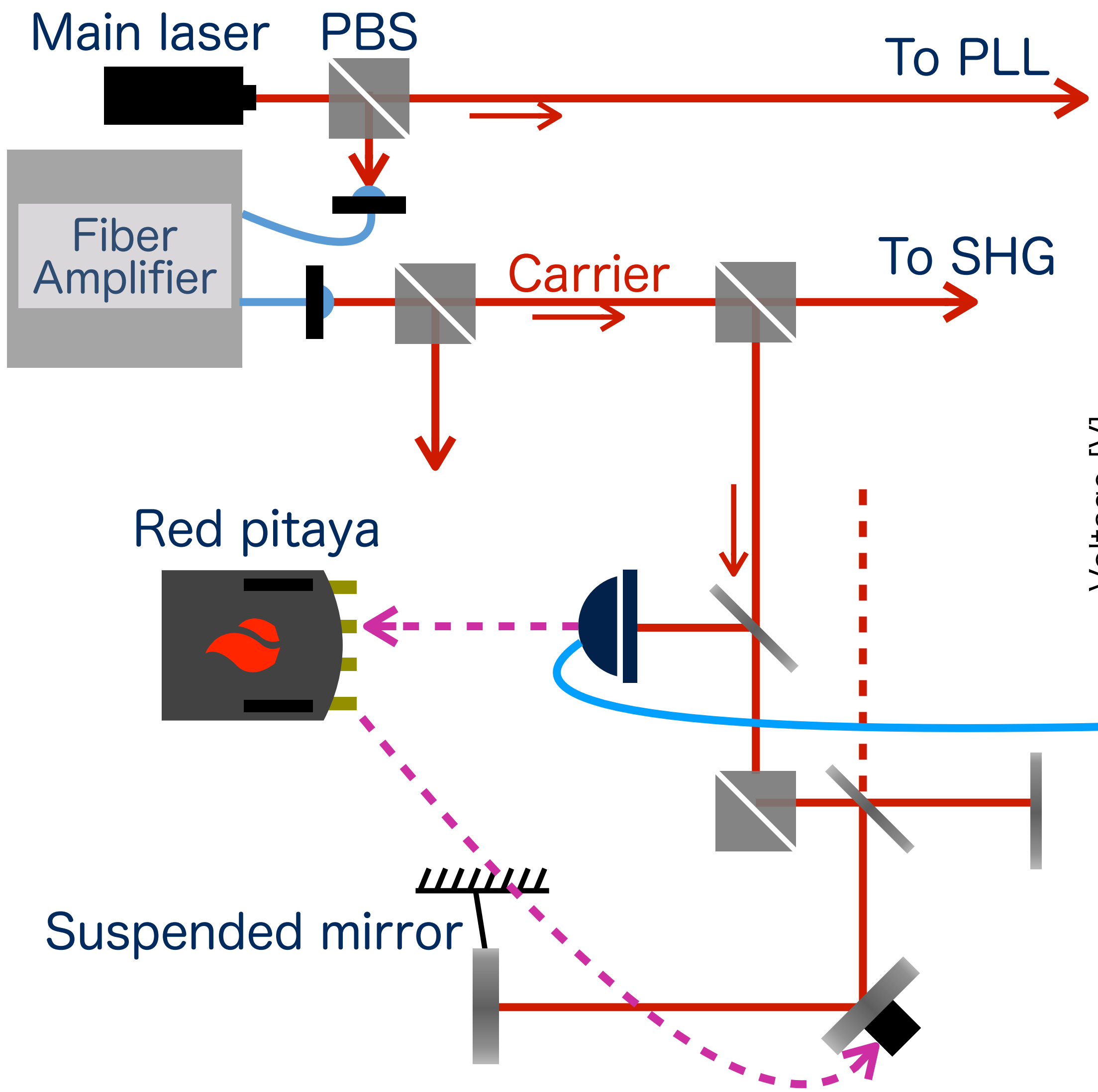
SR mirror

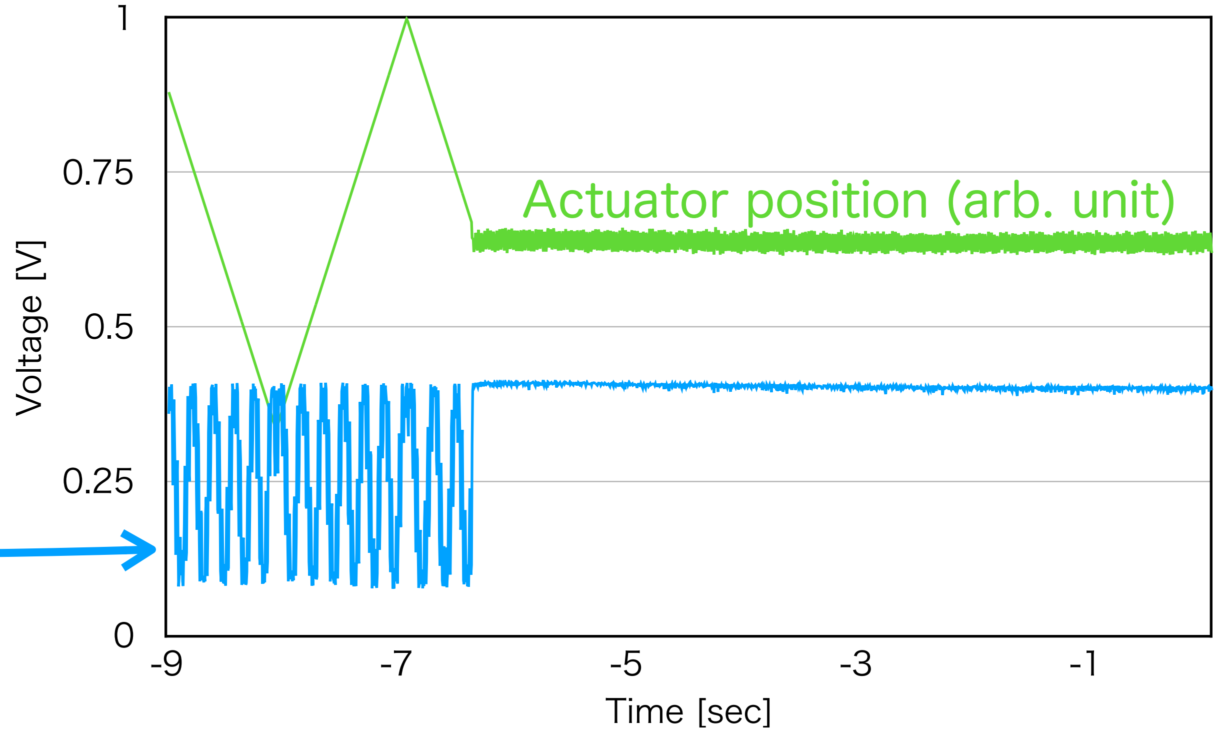
Cavity
to generate
pump light
(532nm, Green)

Experimental flowchart

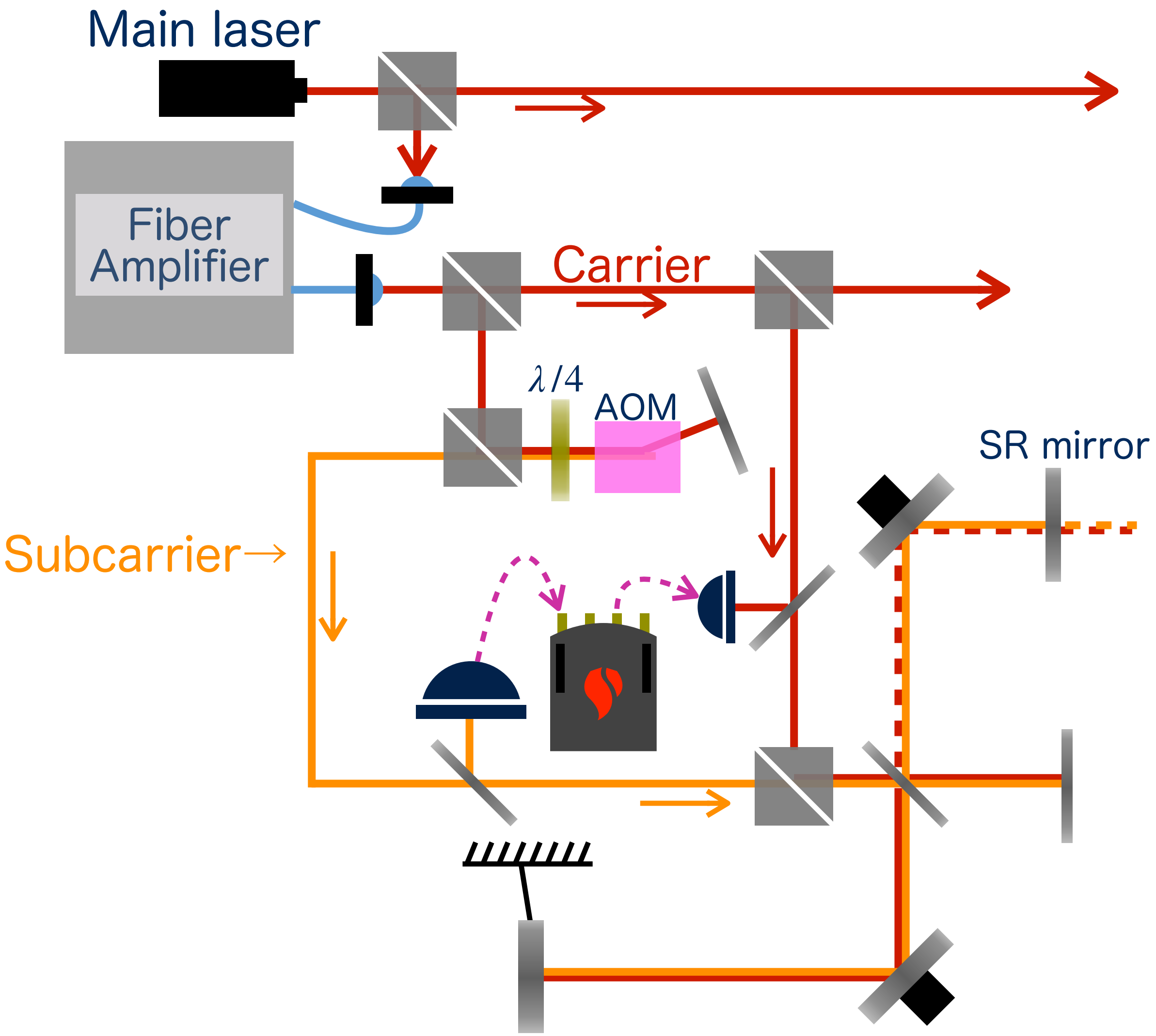


Control scheme; differential arm length



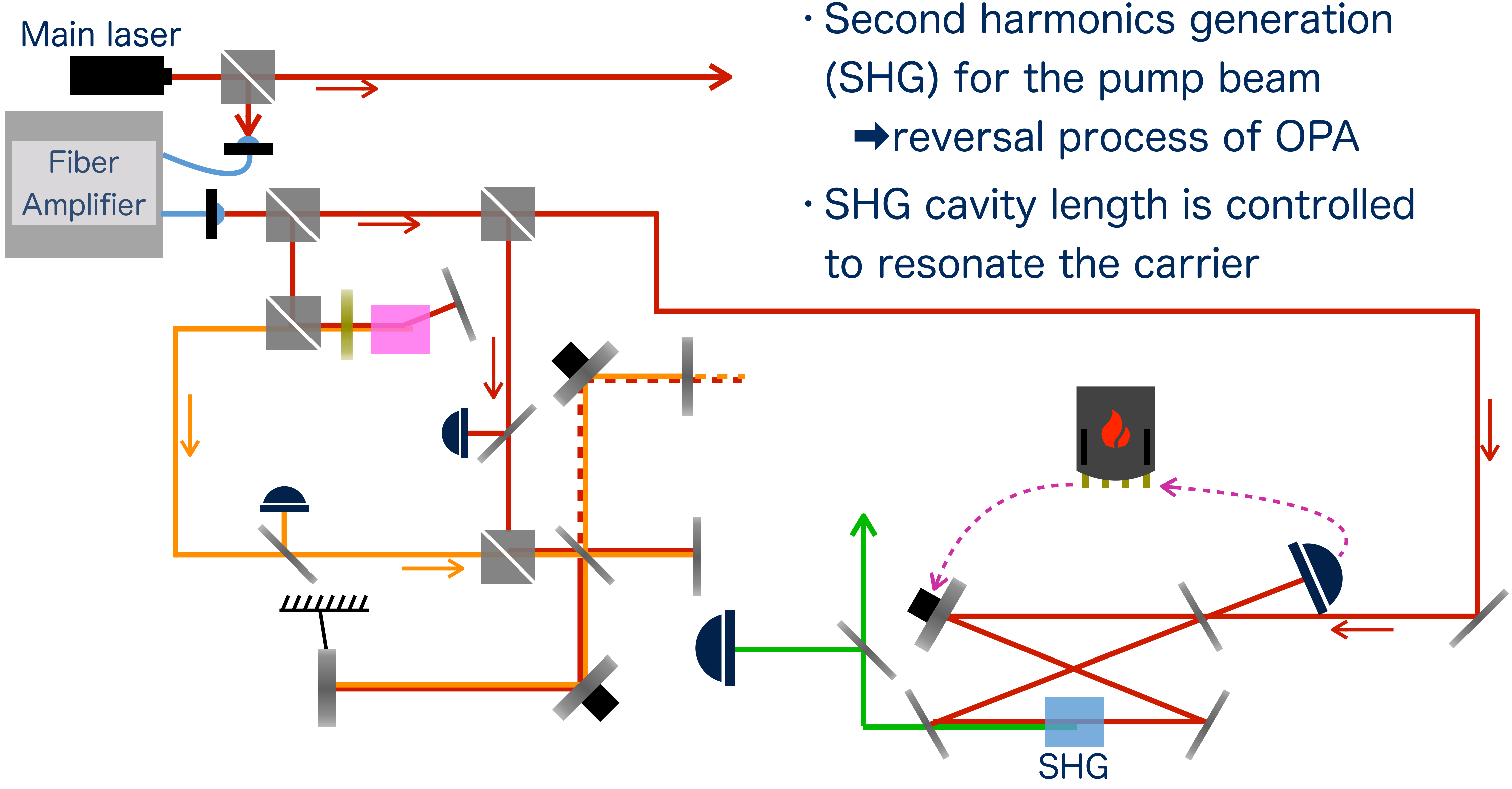


Control scheme; SR cavity length



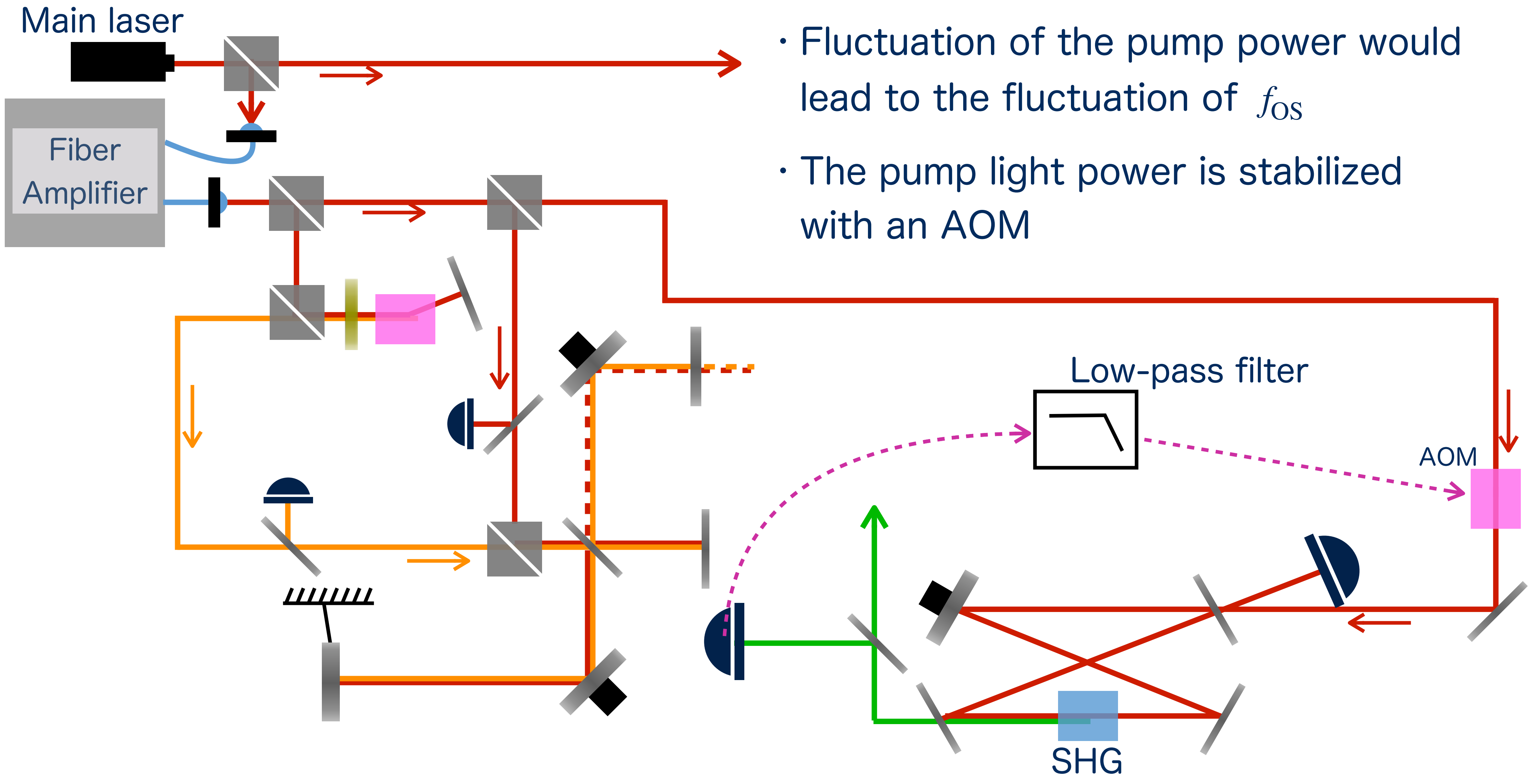
- Subcarrier frequency is shifted by ~100MHz with an AOM.
- SR cavity length is locked to a resonance of the subcarrier

Control scheme; Pump light generation



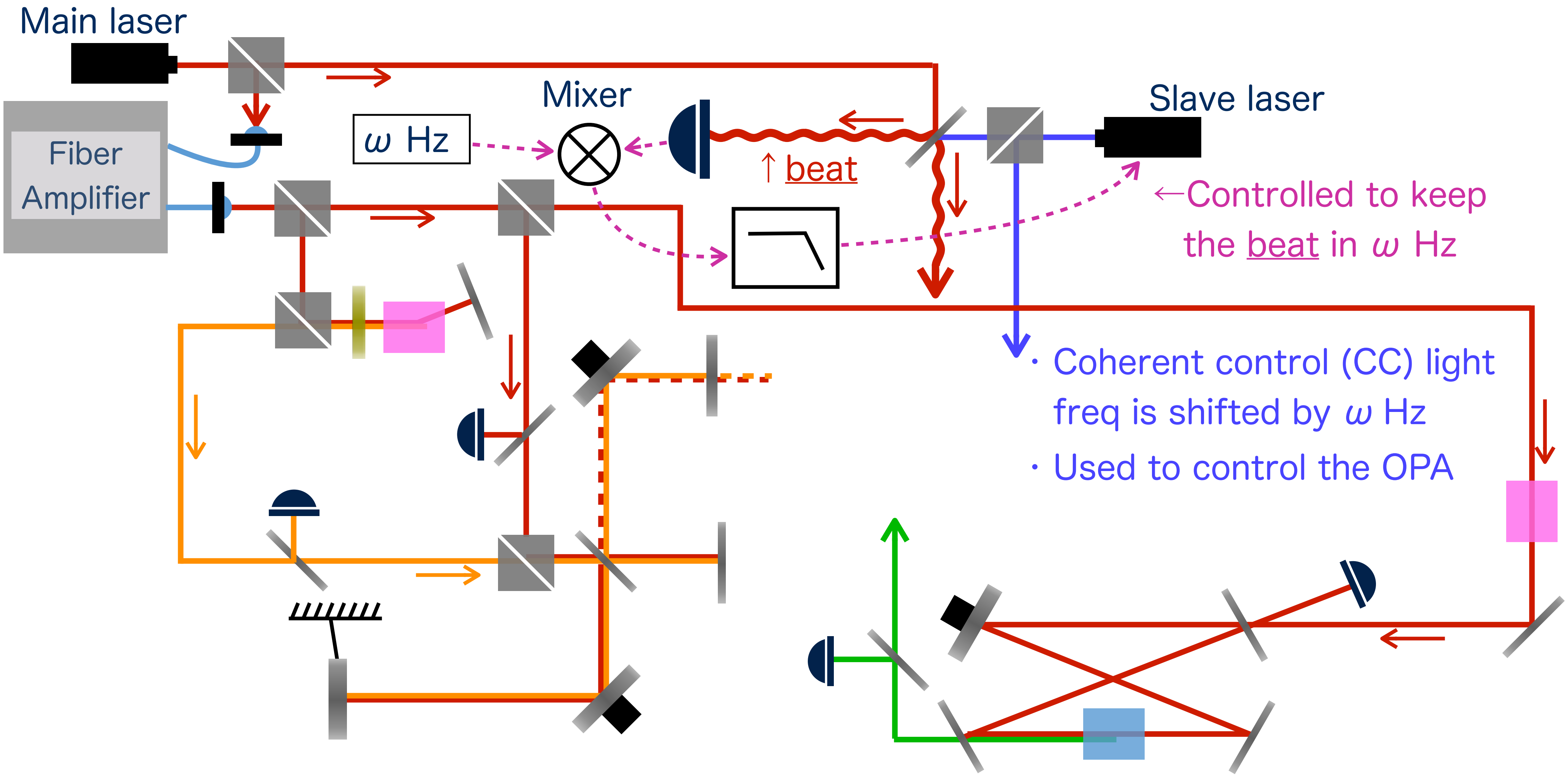
- Second harmonics generation (SHG) for the pump beam
  ➡reversal process of OPA
- SHG cavity length is controlled to resonate the carrier

Control scheme; Pump light power stabilization



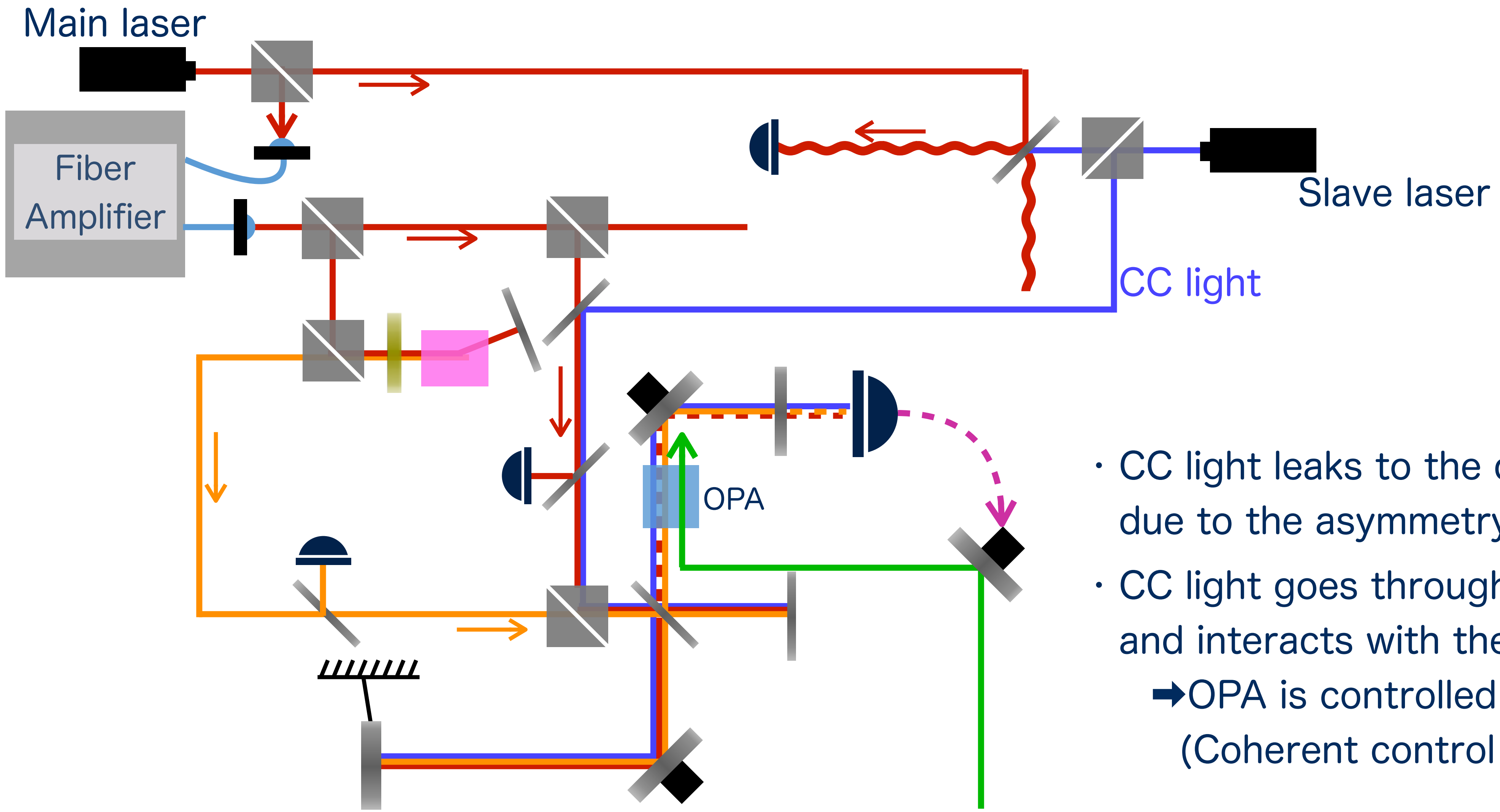
- Fluctuation of the pump power would lead to the fluctuation of f_{OS}
- The pump light power is stabilized with an AOM

Control scheme; CC light generation



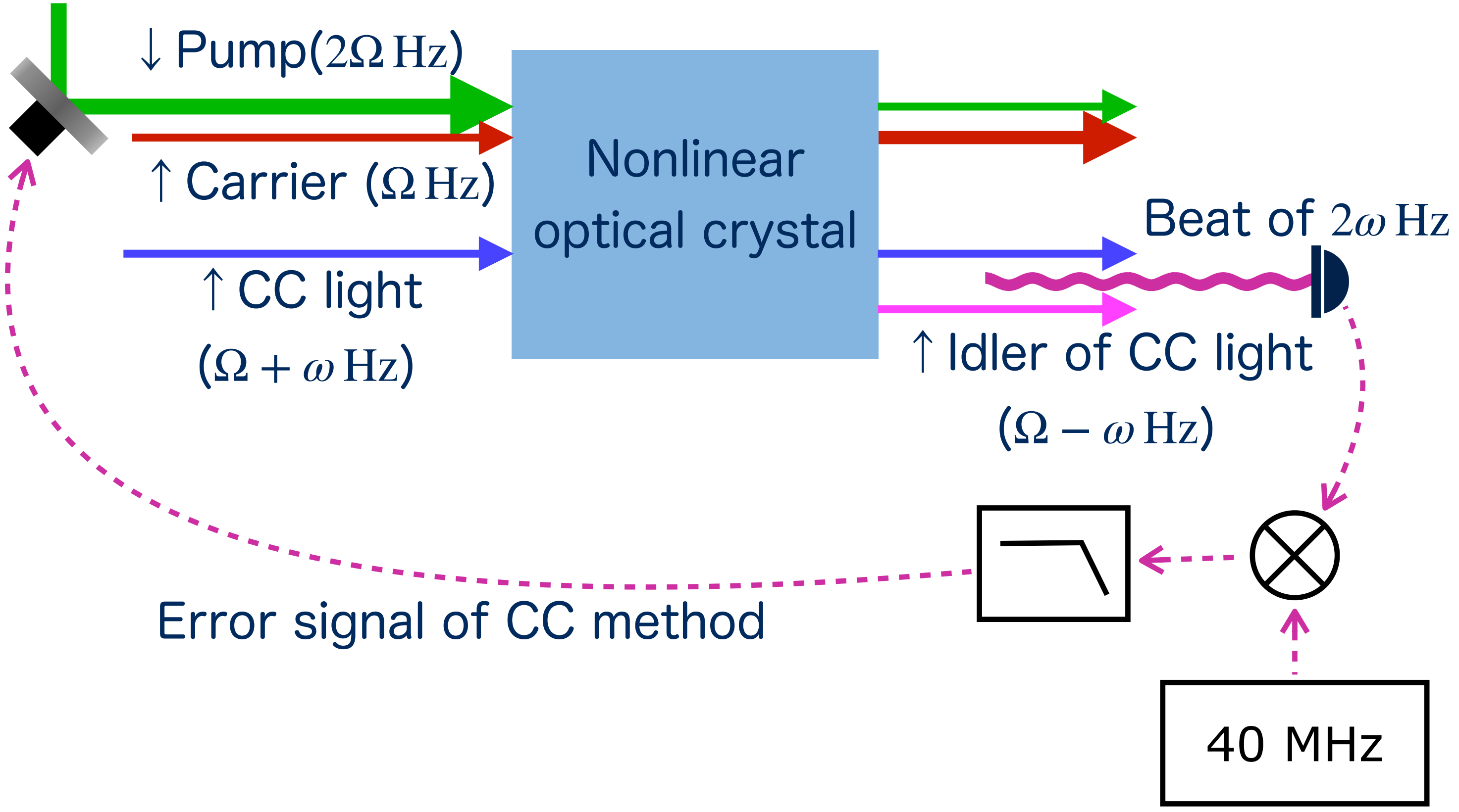
- Coherent control (CC) light freq is shifted by ω Hz
- Used to control the OPA

Control scheme; phase controll of pump light



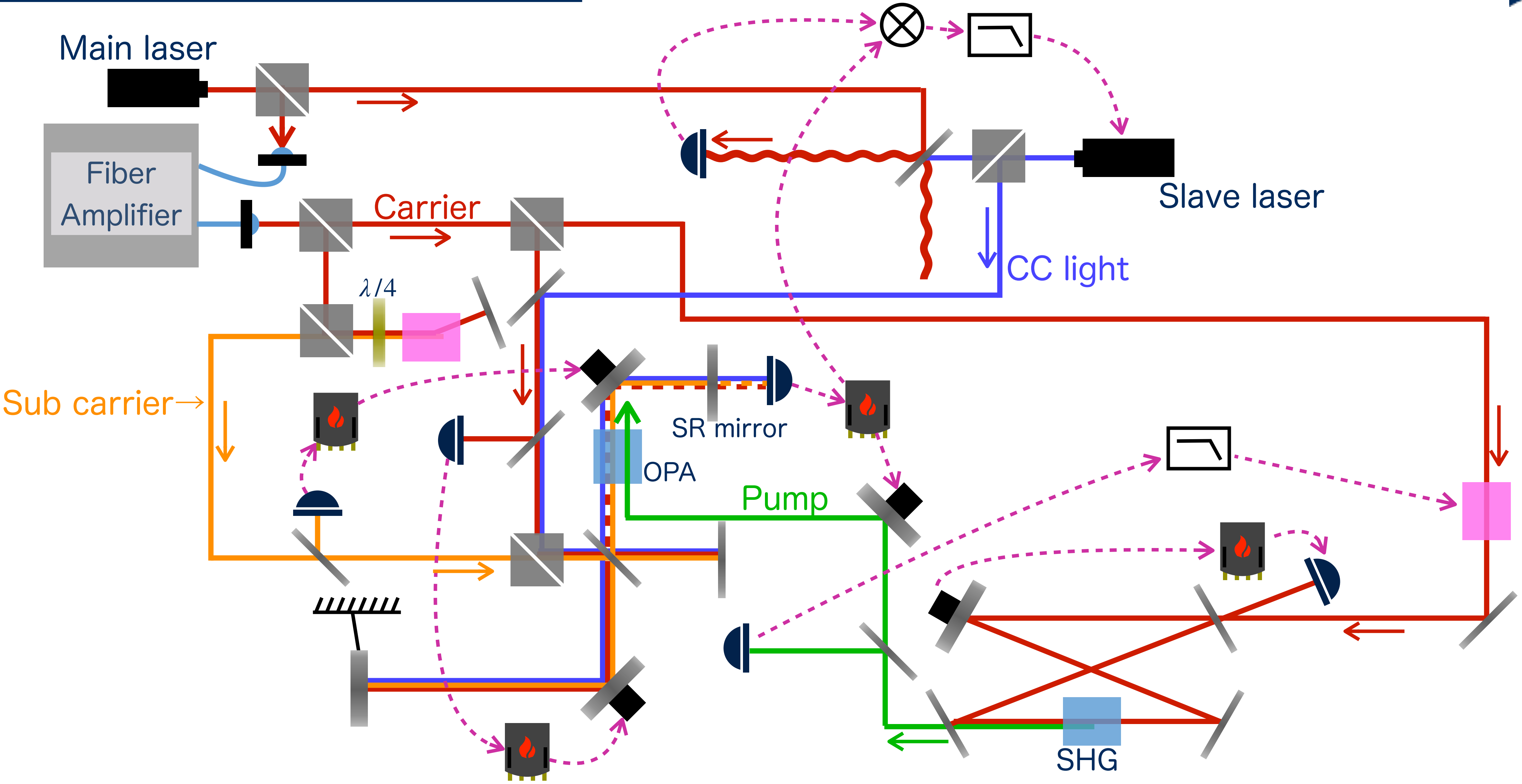
- CC light leaks to the dark port due to the asymmetry
- CC light goes through the OPA and interacts with the pump
  ➡OPA is controlled by CC light
  (Coherent control method)

Coherent control method

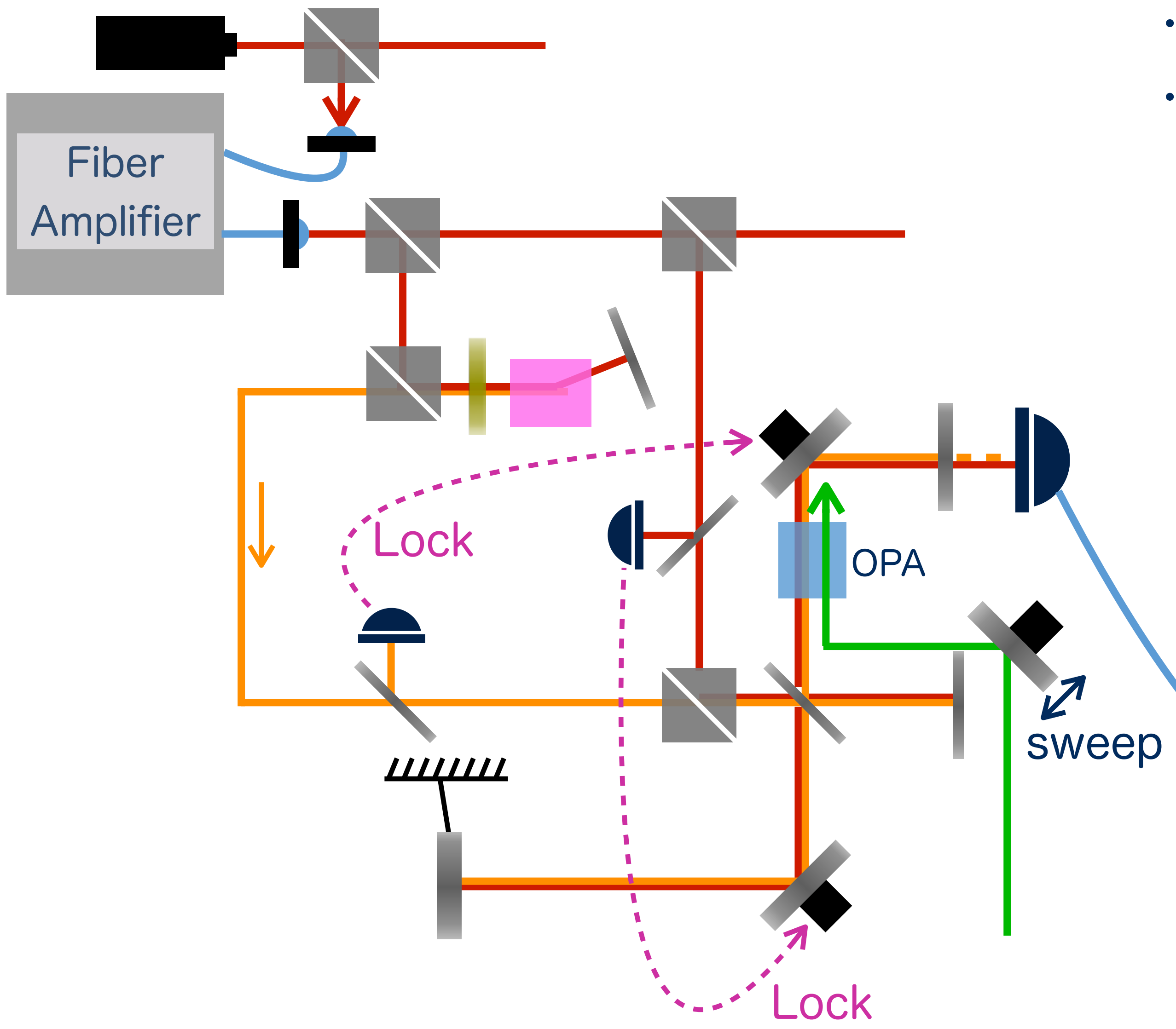


- -ω shifted light is generated by nonlinear optical effects ($\omega_{\mathrm{idler}} = \omega_{\mathrm{pump}} - \omega_{\mathrm{signal}}$) on ω shifted light(CC light)
- Phase of pump light can be controlled by demodulating the beat of 2ω

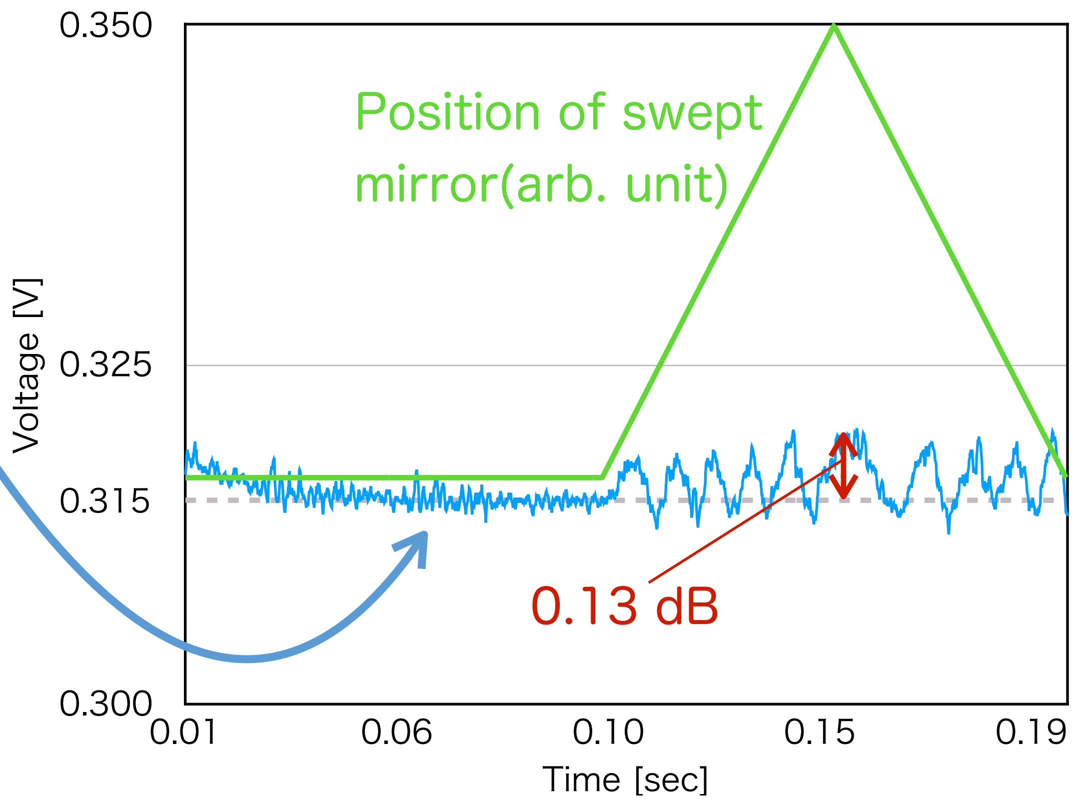
Overview of the whole control system



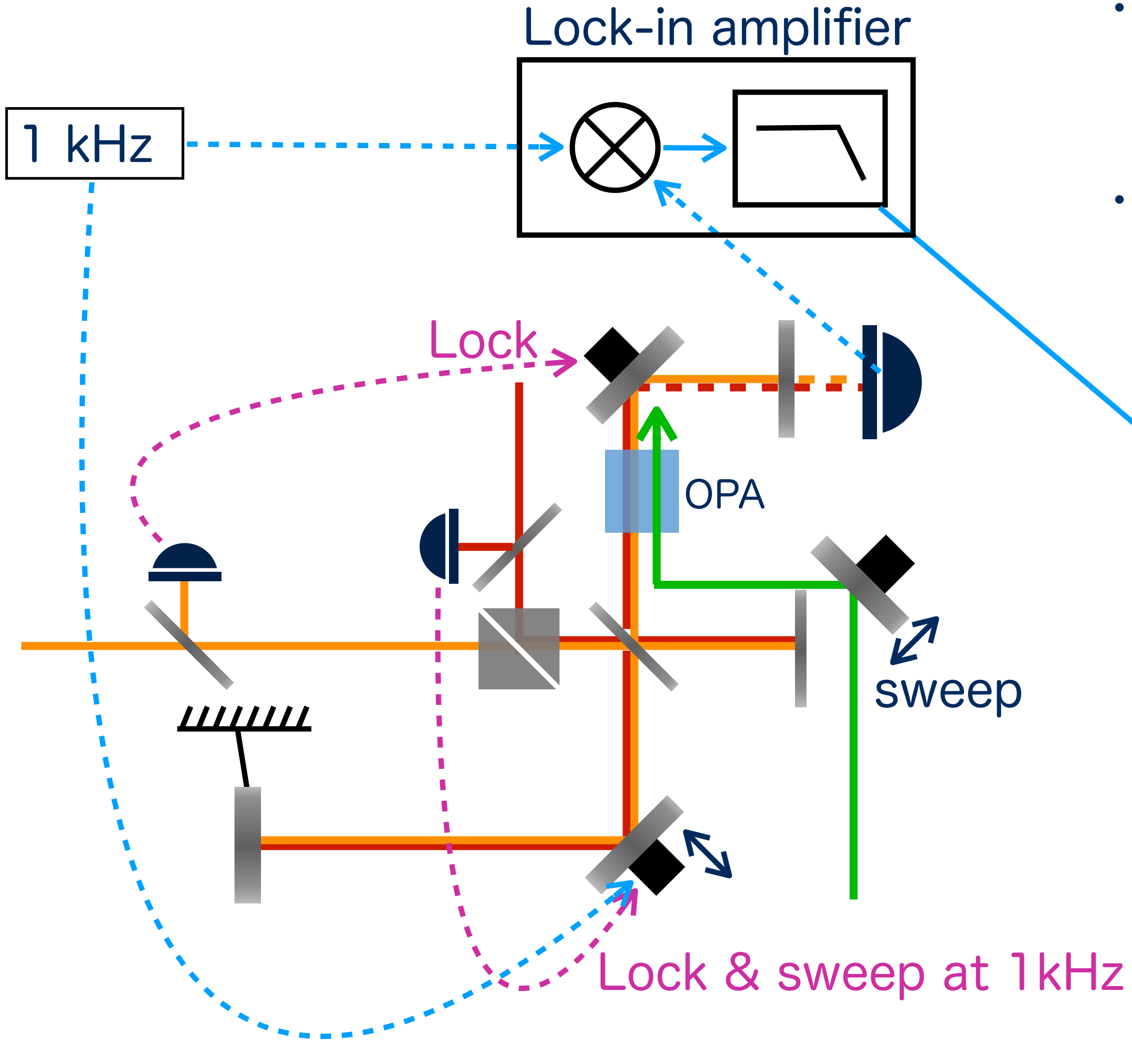
Result; OPA with carrier light



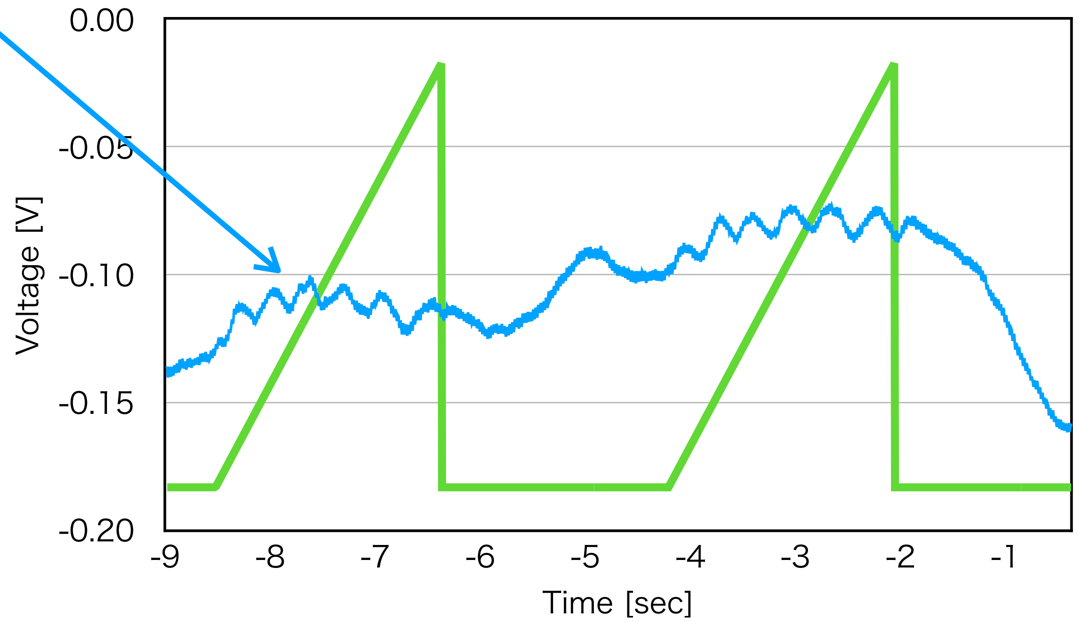
- MI is controlled to be bright
- Amplitude of OPA changes swept pump light phase ↓



Result; OPA with 1kHz signal

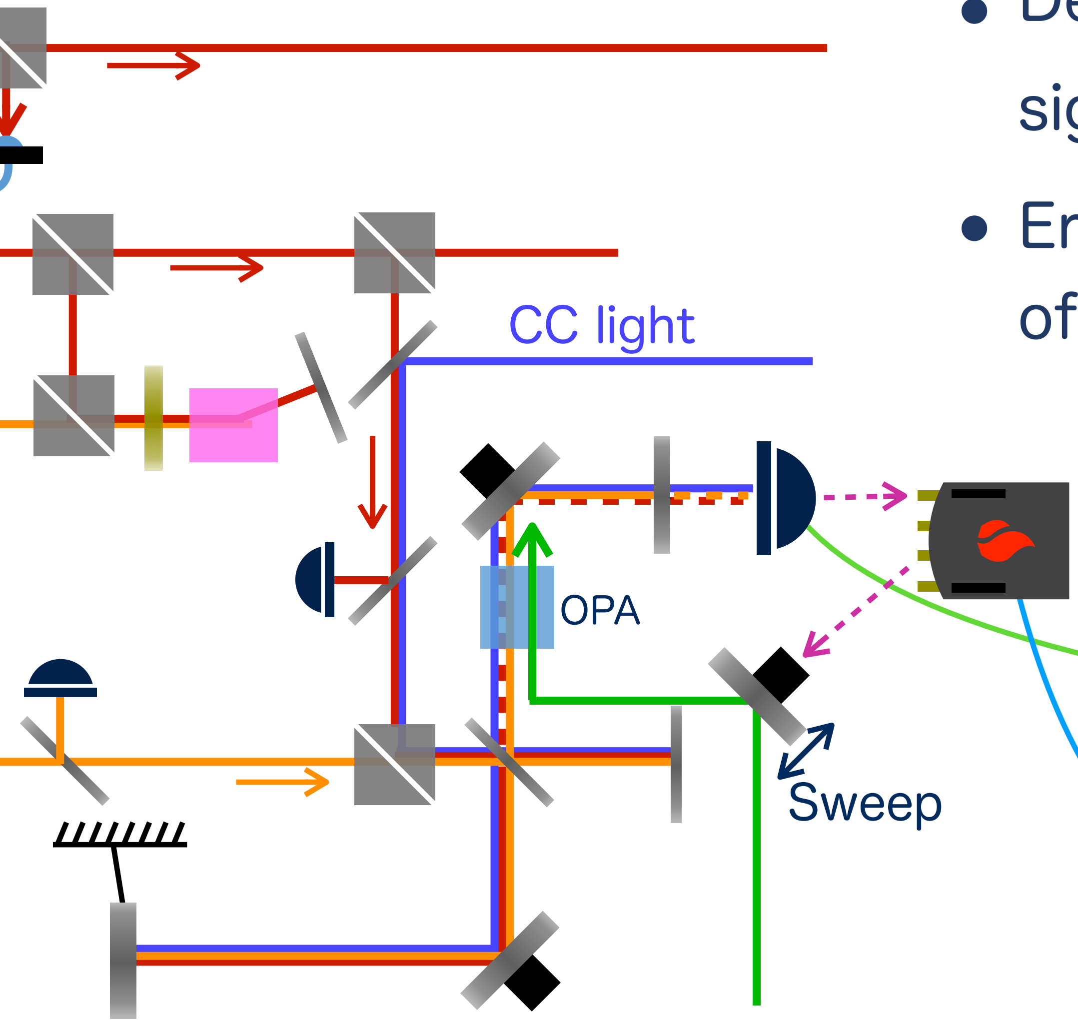


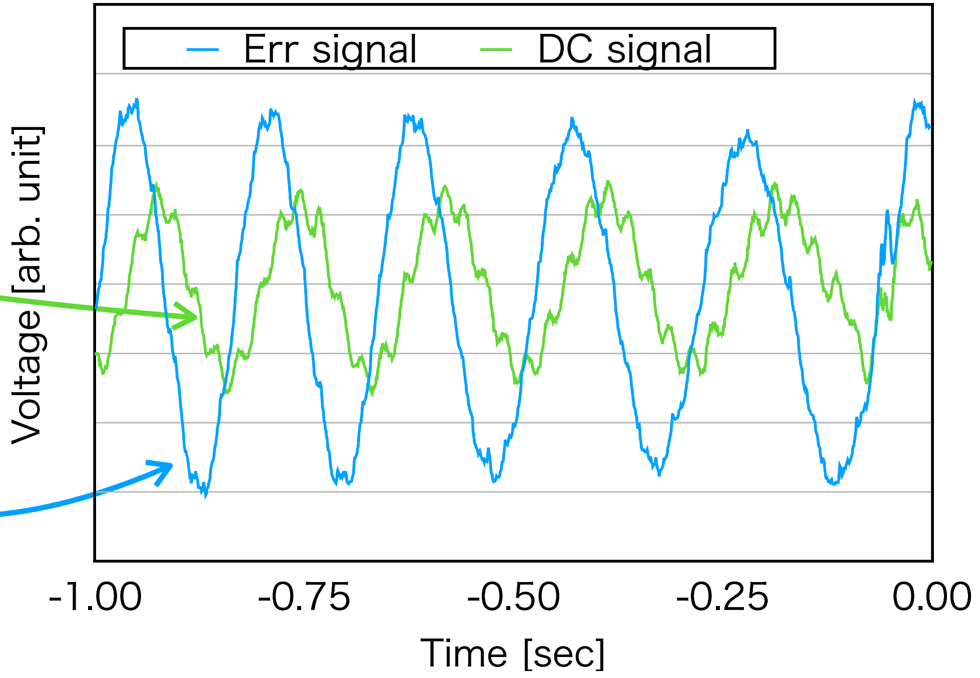
- The 1kHz MI signal is amplified and de-amplified by the intracavity OPA
- There is no local oscillator at the dark port, so the DC signal is fluctuating.



Result; Error signal of CC method

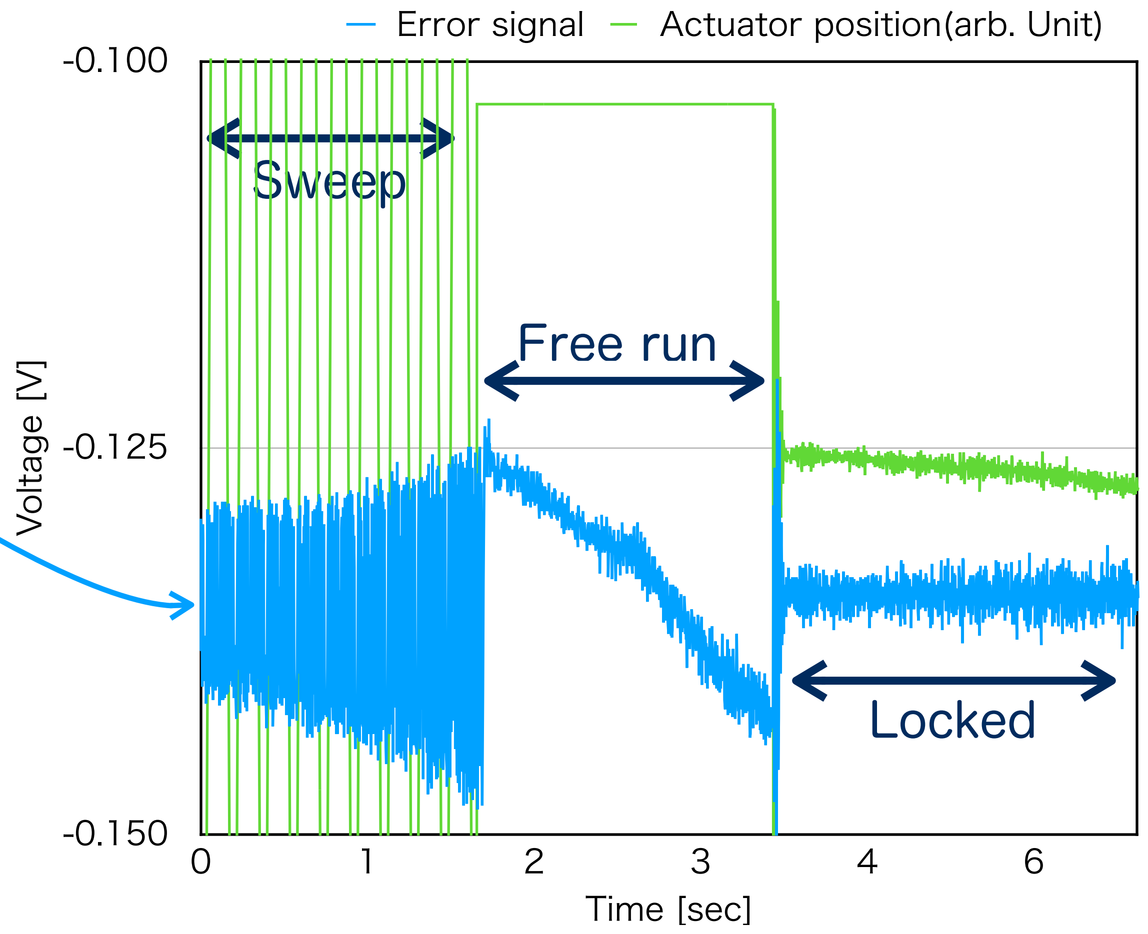
- Demodulate the $40\,\mathrm{MHz}$ $(:= 20\,\mathrm{MHz} - (-20\,\mathrm{MHz}))$ signal in the red pitaya
- Error signal is linear at the peak of OPAed DC signal





Result; Phase locking of pump light

- Successful control of the OPA using the CC method has been confirmed through the stabilization of the error signal
- We will measure the Michelson signal at the dark port with a local oscillator to verify the signal amplification soon



Summary

- Our goal is to verify the sensitivity enhancement in high frequency band of gravitational detector combining optical spring and nonlinear optical effects
- 6-DoF control was realized by using single-board computers
- Phase of the OPA was successfully controlled by coherent control method

Future works

- Verifying control of OPA with Michelson signal at dark port
- Measuring the transfer function and observe the optical spring