Current status and future plans for DANCE

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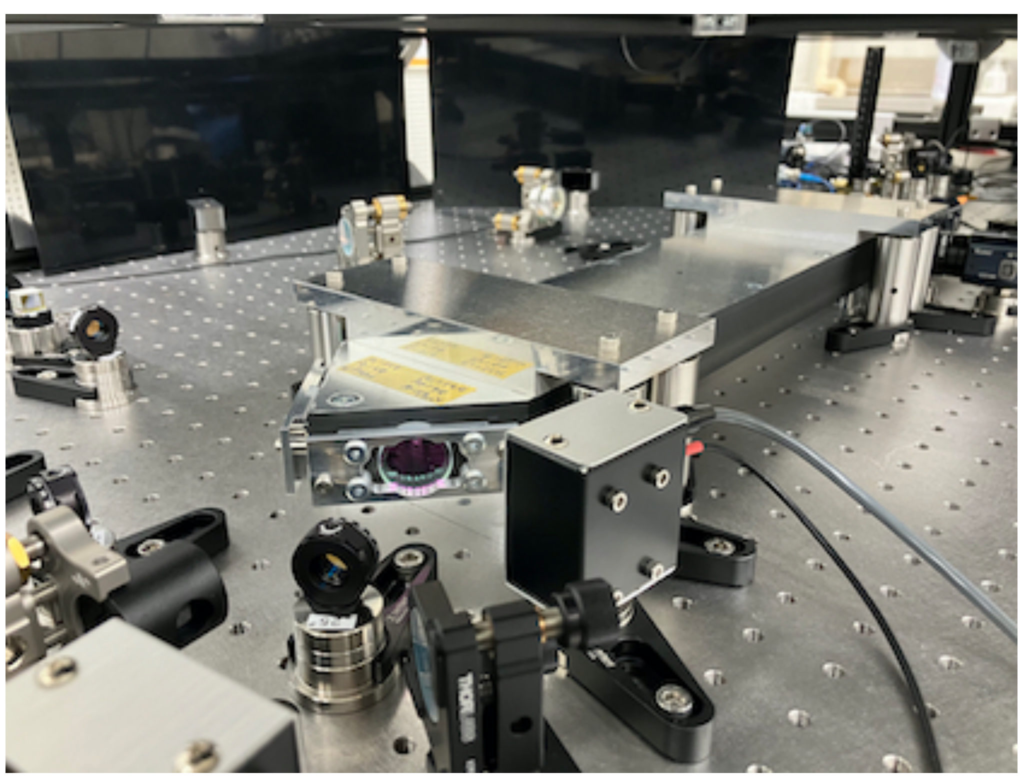
Abstract

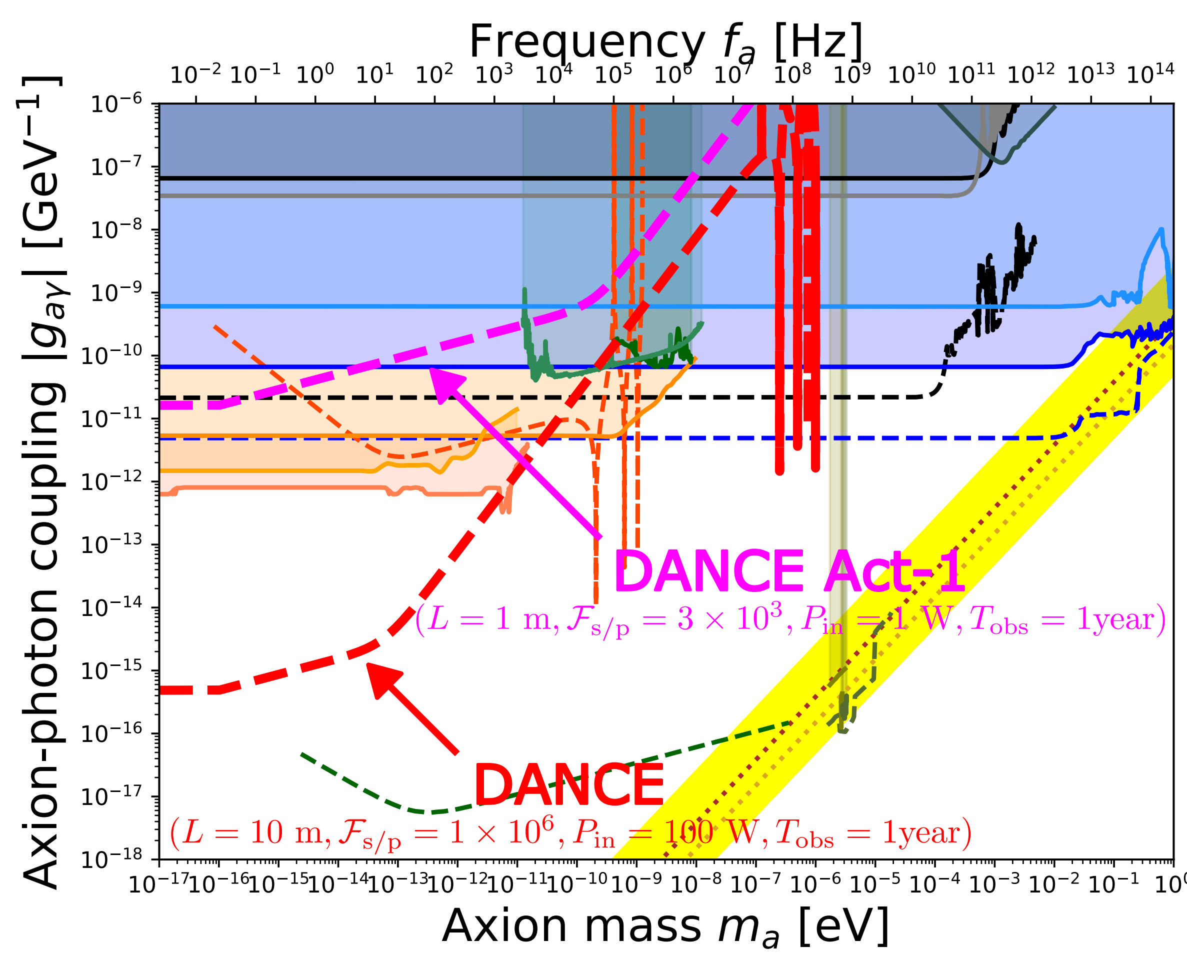
Aim to detect axion with a bow-tie optical ring cavity

- Laser interferometer
- Axion-photon interaction
- Simultaneous resonance

⟹ Conduct a sensitive broadband axion search

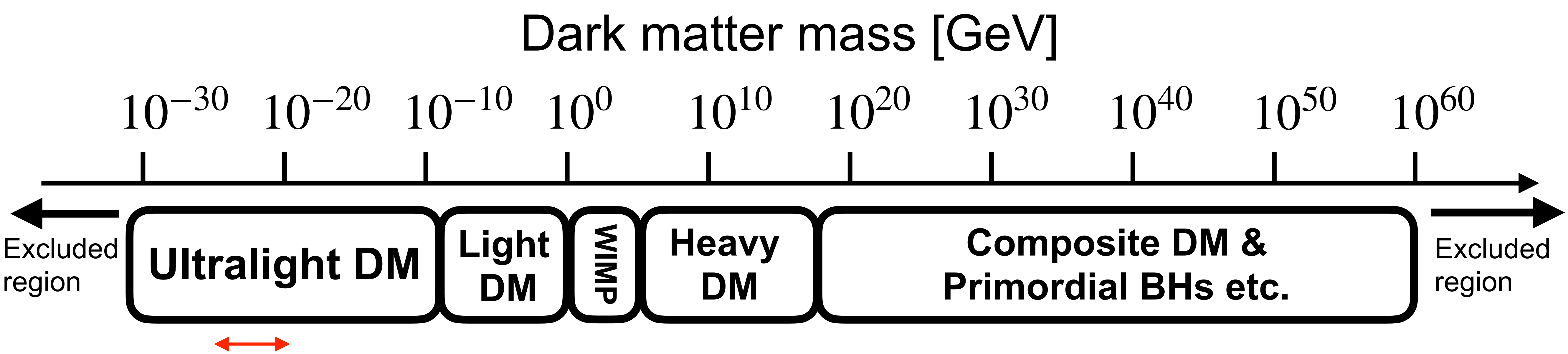


DANCE

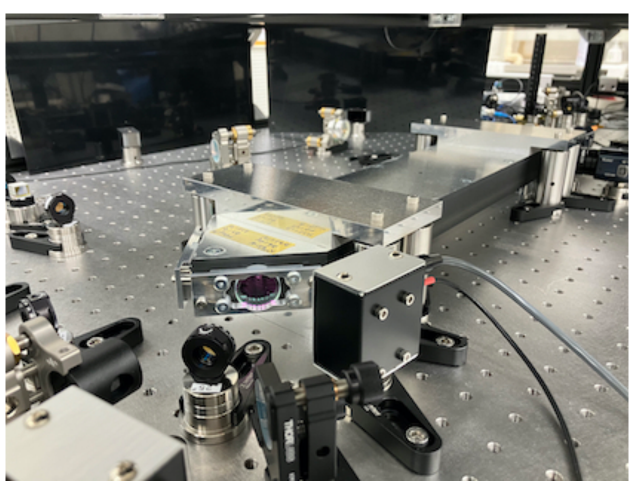


Dark matter

- Account for about 80% of all the matter in the universe
- Extensive research is being conducted
- One of the leading candidates of dark matter: Axion



Laser interferometer



DANCE

KAGRA

XENON

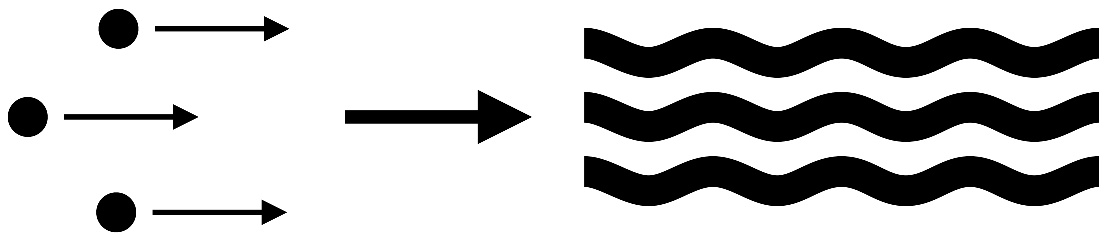
Subaru telescope

Axion and Axion-Like-Particles (ALPs)

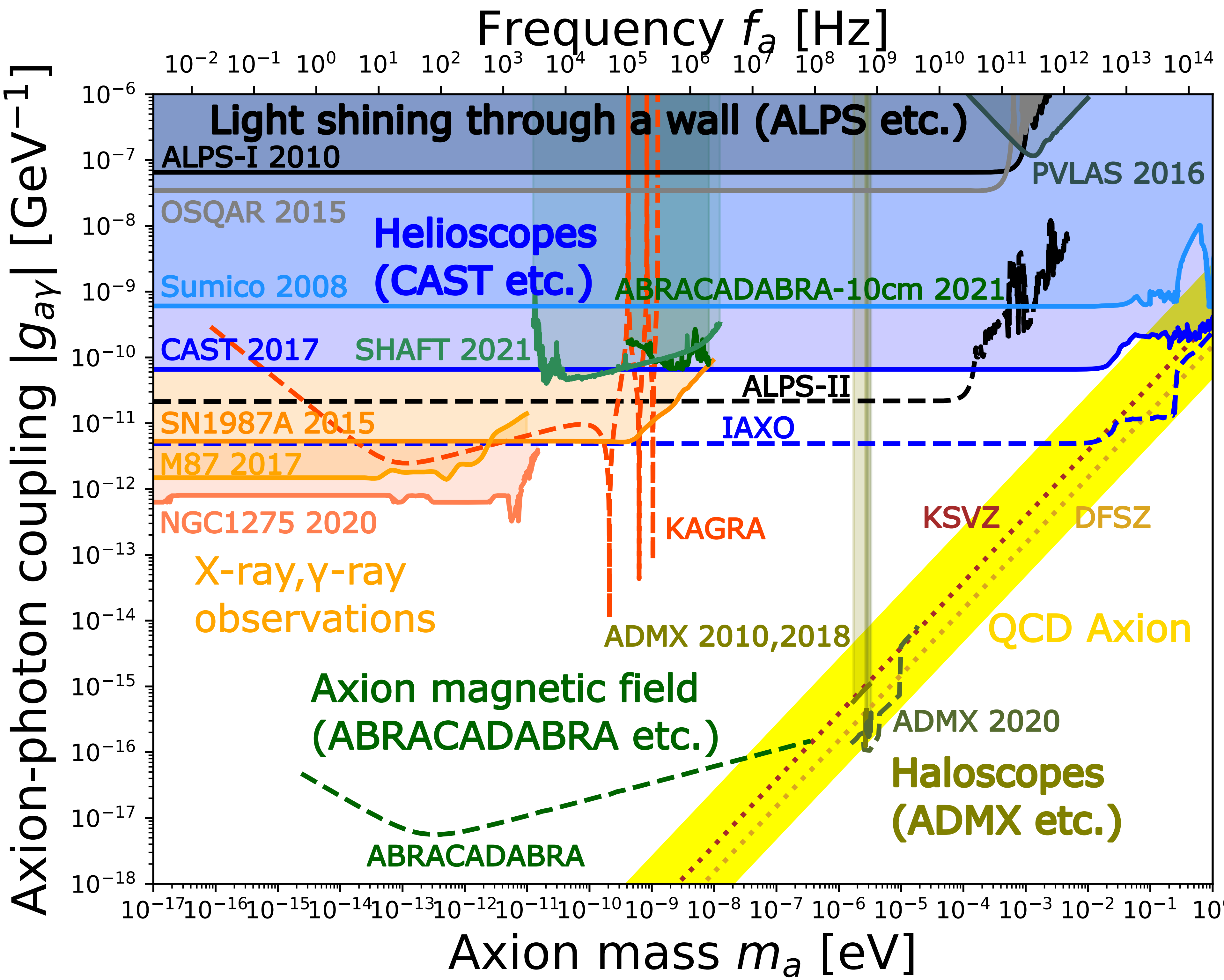
- Pseudo-scalar particle (QCD axion) is suggested to solve strong CP problem on Quantum Chromo Dynamics (QCD)
- Various Axion-Like-Particles (ALPs) is predicted
- Many experiments have utilized the axion-photon conversion under magnetic field (Primakoff effect). However, axion has not been observed yet.

<u>Characteristics (ALPs)</u>

- Very light particles ⇒ Behave like waves
- Axion weakly interacts with photon, electron, proton



Previous searches



Relation between axion mass and frequency

$$f_a = \frac{m_a}{2\pi\hbar}\ [\mathrm{Hz}]$$

Axion-photon interaction

Axion-photon interaction induces phase velocity difference between left-handed and right-handed circularly polarized light

$$c_{\mathrm{L/R}}(t) = 1 \pm \frac{g_{a\gamma} a_0 m_a}{2k} \sin(m_a t + \delta_\tau)$$

Axion mass

Phase velocity

Axion-photon coupling

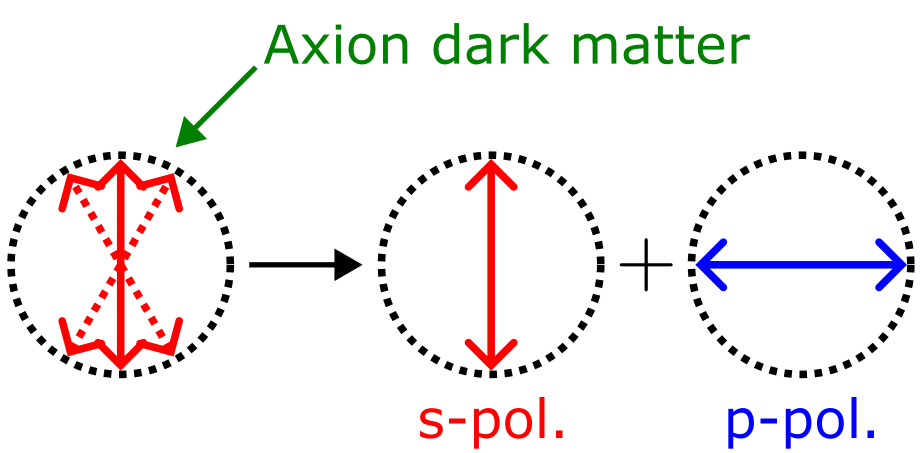
Axion field

Phase factor

→ Regard as a rotation of linearly polarized light

Rotation angle of linearly polarized light

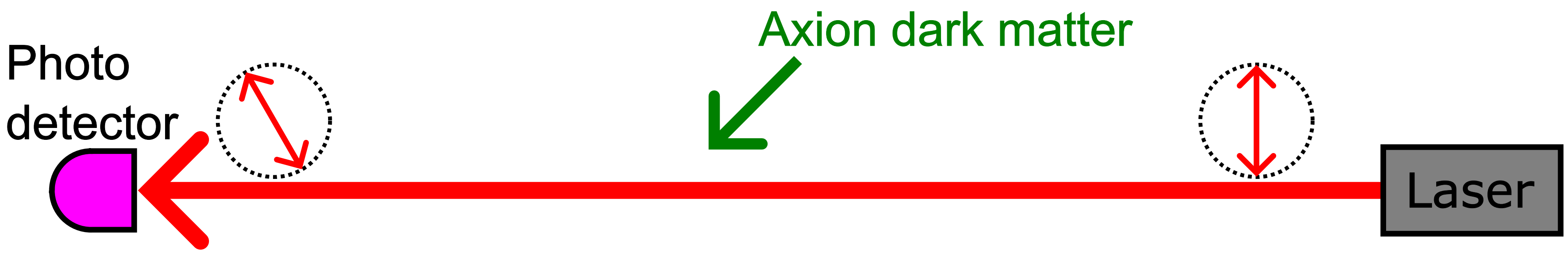
$$\Delta\theta(l,t) = \frac{g_{a\gamma}\sqrt{2\rho_a}}{m_a} \sin\left(m_a \frac{l}{2}\right) \sin\left(m_a\left(t - \frac{l}{2}\right) + \delta_\tau\right)$$



- Detect p-polarized light (Axion signal)
- Amplify it by using longer optical path

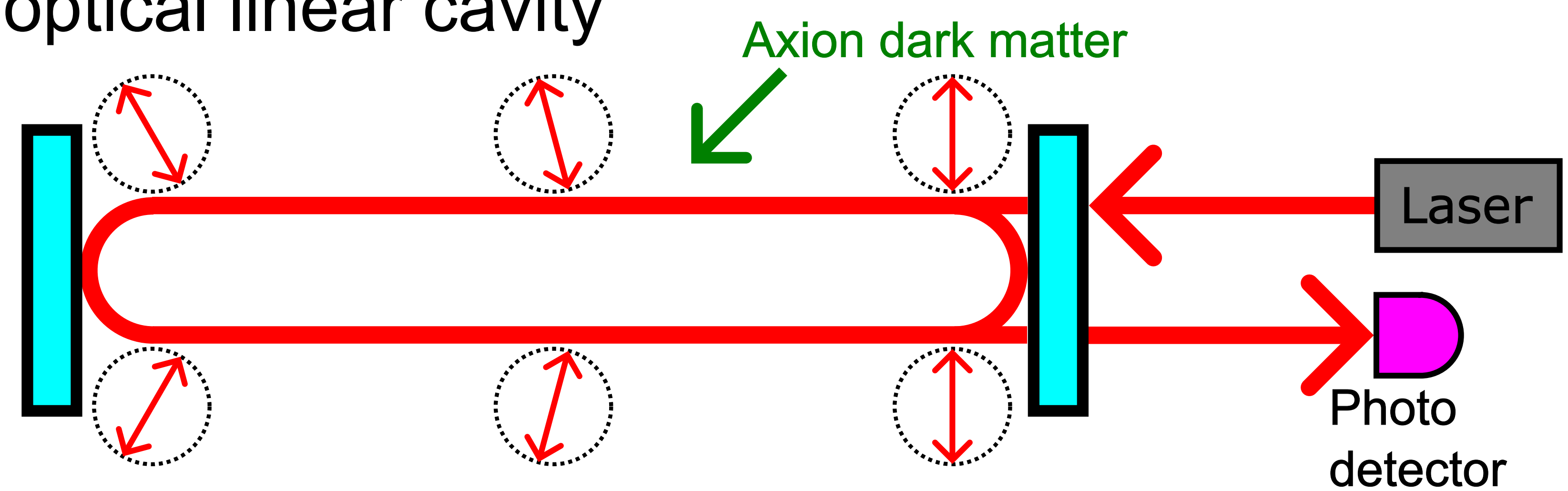
How to amplify the axion signal

Rotation of polarization is small for short optical path



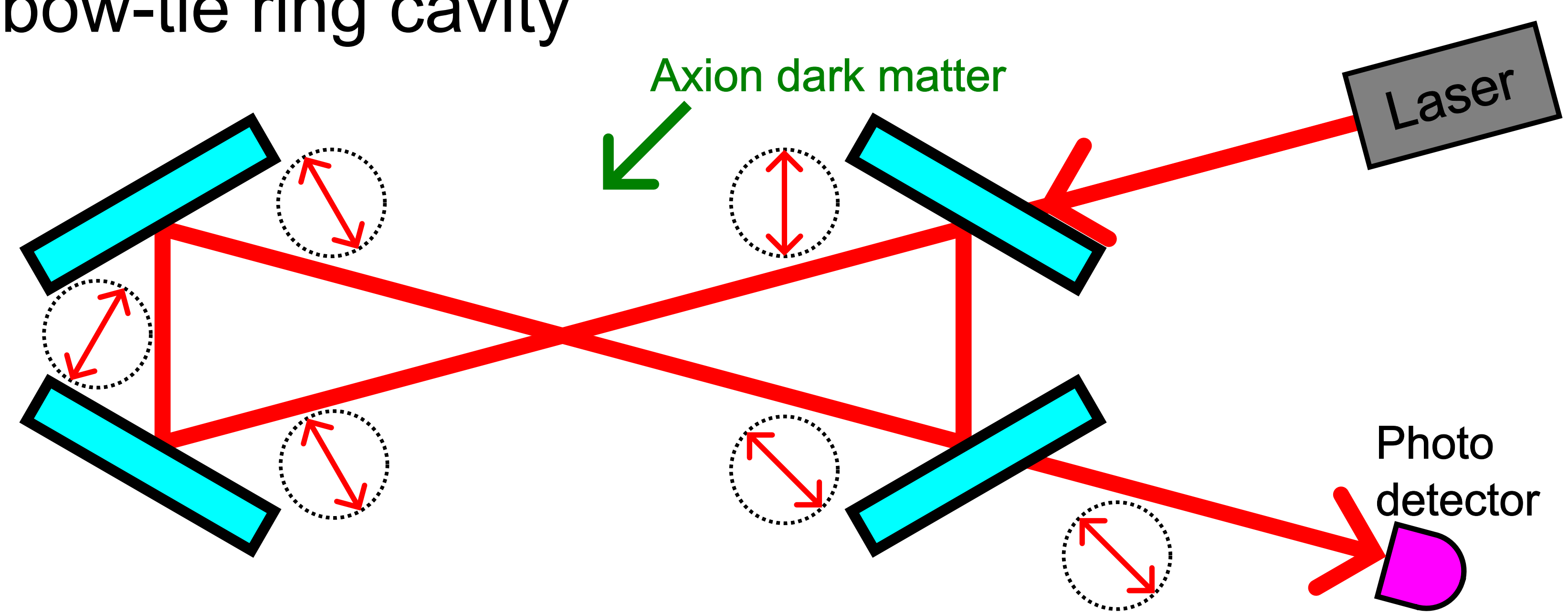
Extend optical path with a optical linear cavity

However, rotation of polarization can not be amplified because it is flipped by reflections



Extend optical path with a bow-tie ring cavity

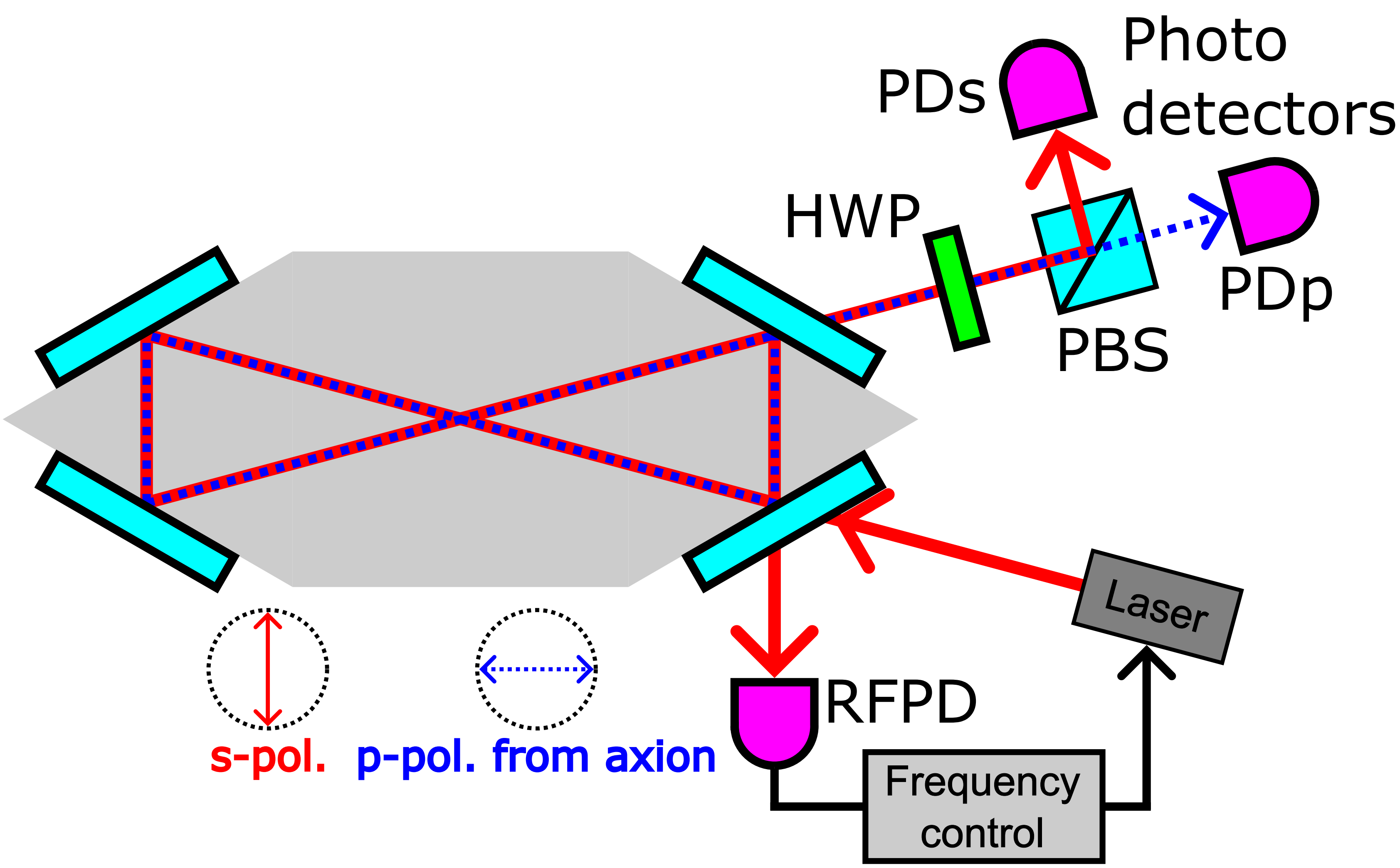
Rotation of polarization can be amplified because the flip is canceled by reflections on both two mirrors



DANCE

DANCE (Dark matter Axion search with riNg Cavity Experiment)

- Dark matter axion search with laser interferometer technique
- Bow-tie optical ring cavity

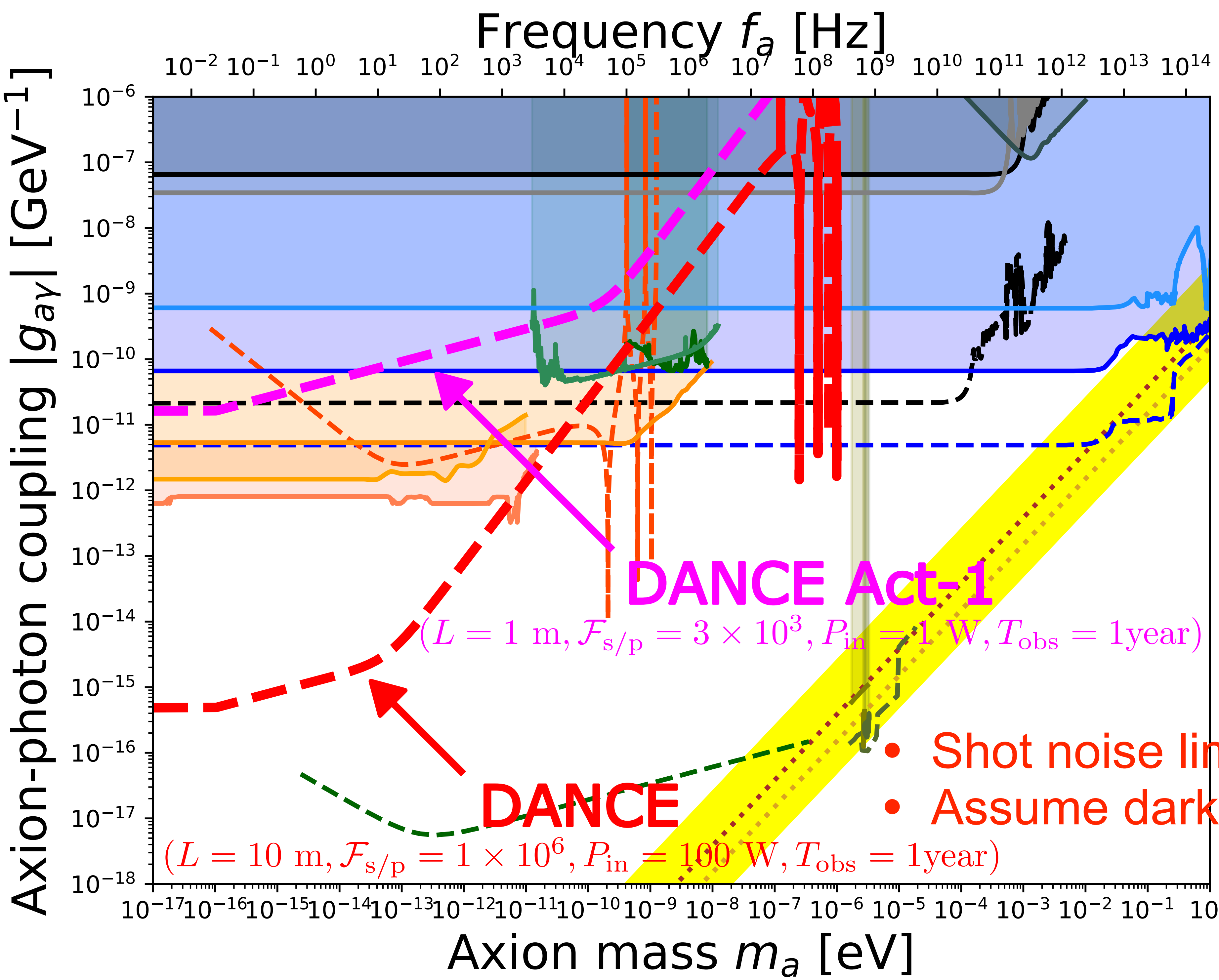


Measure the amount of modulated p-polarized light (Axion signal) by amplifying it with a bow-tie optical ring cavity

Target sensitivity of DANCE

Aim to detect axion dark matter in low mass region

L: round-trip, $\mathscr{F}_{\mathrm{s/p}}$: finesse s/p-pol., P_{in}: Input power



- Shot noise limit
- Assume dark matter is Axion

Contents

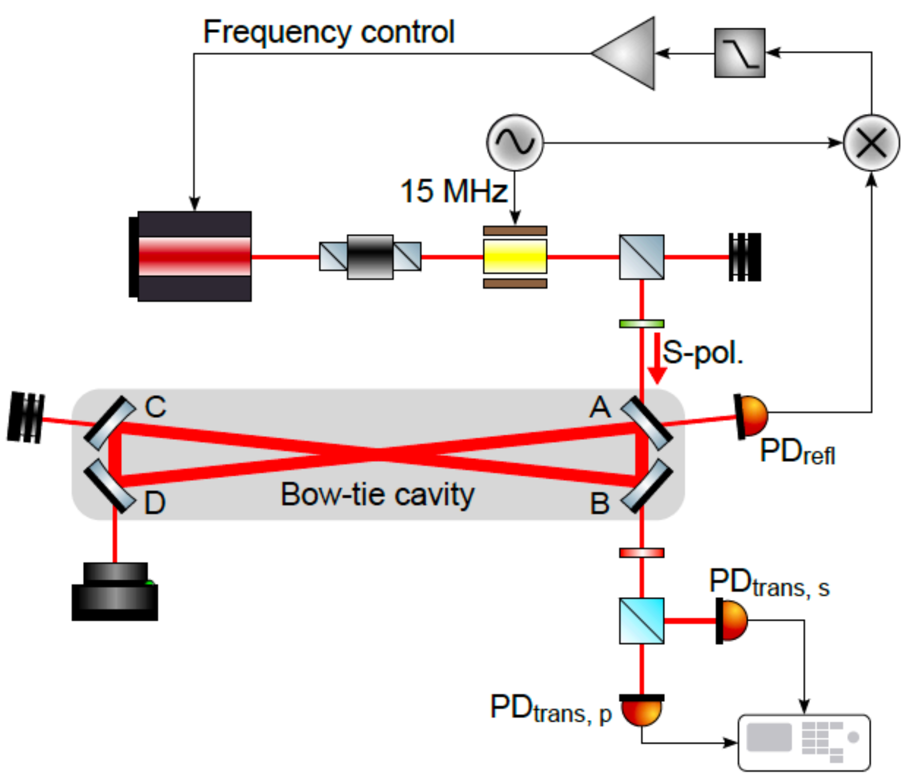
- Introduction
- **Current status of DANCE**
- Current status of my experiment
- Future plans for DANCE
- Summary

Current status of DANCE Act-1

- Started in 2019 ⇨ First observation was finished in May 2021
- Issue: s-pol. and p-pol. do not resonate simultaneously

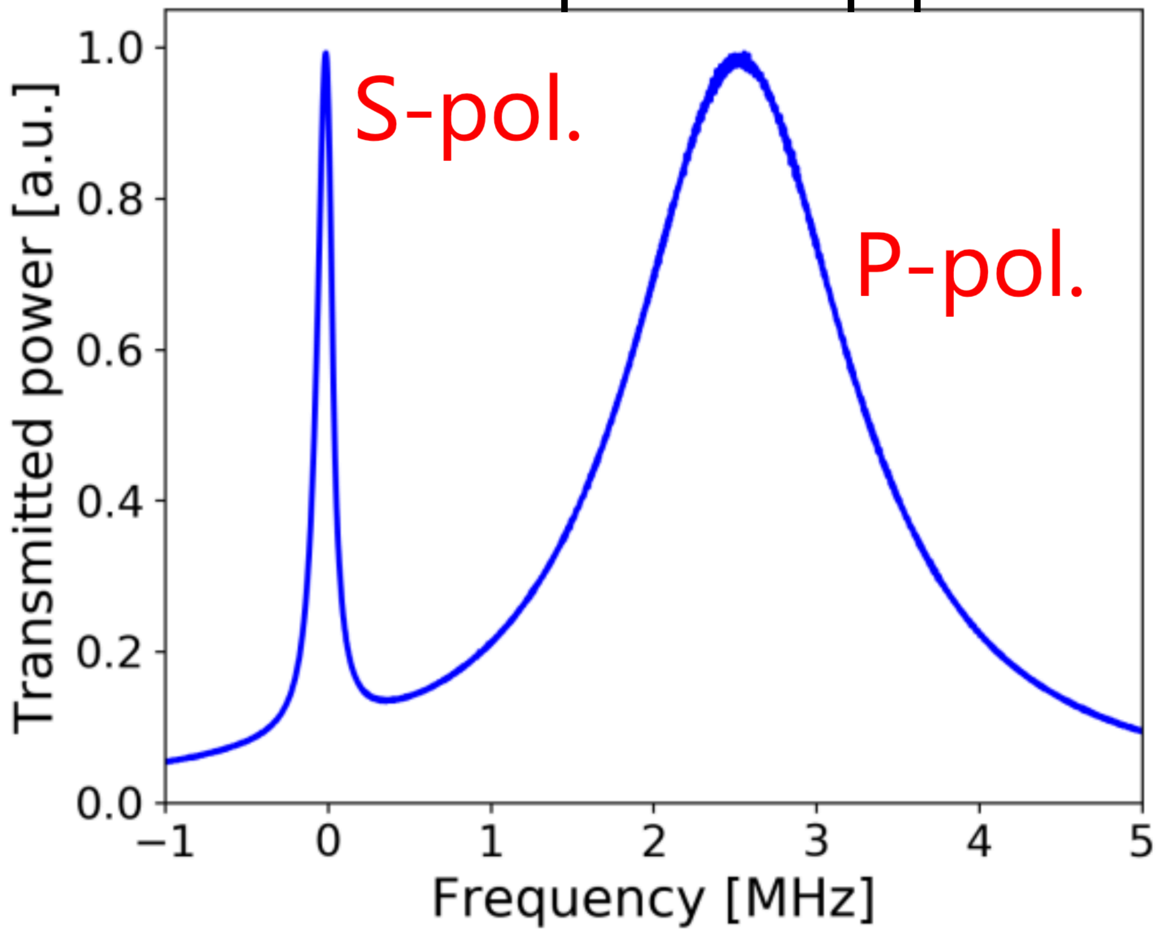
⇨ Degrade the sensitivity to axion in low axion mass region

- Achieved simultaneous resonance for the first time with an auxiliary cavity in November 2021



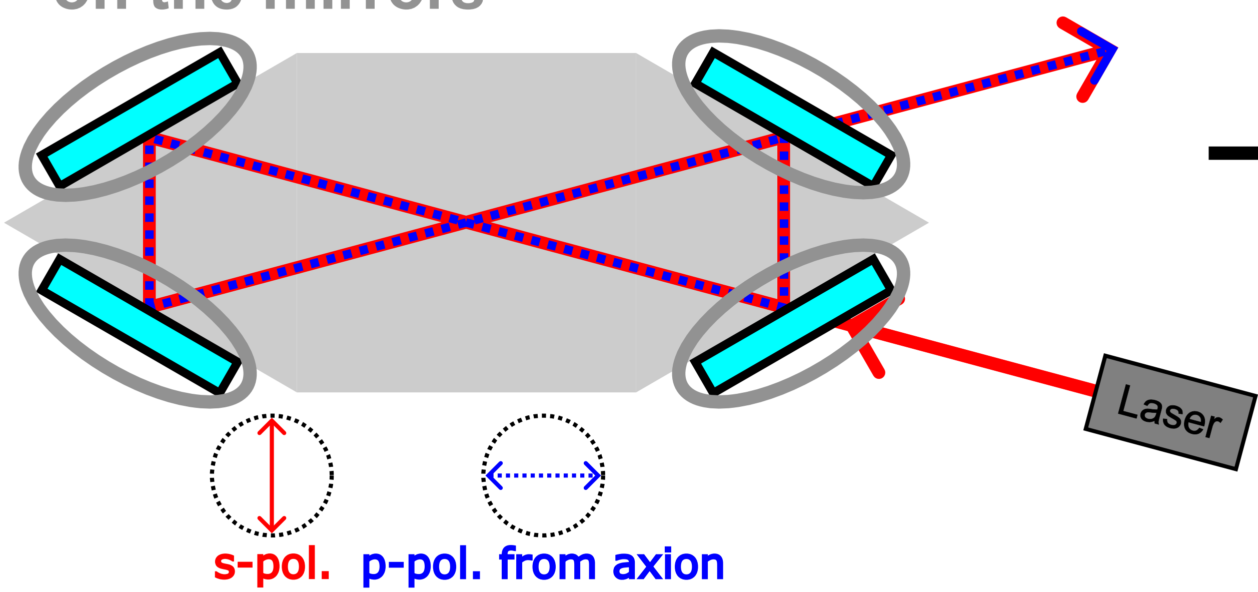
Y. Oshima *et al.*: Phys. Rev. D. **108**, 072005 (2023).

No simultaneous resonance between s-pol. and p-pol.

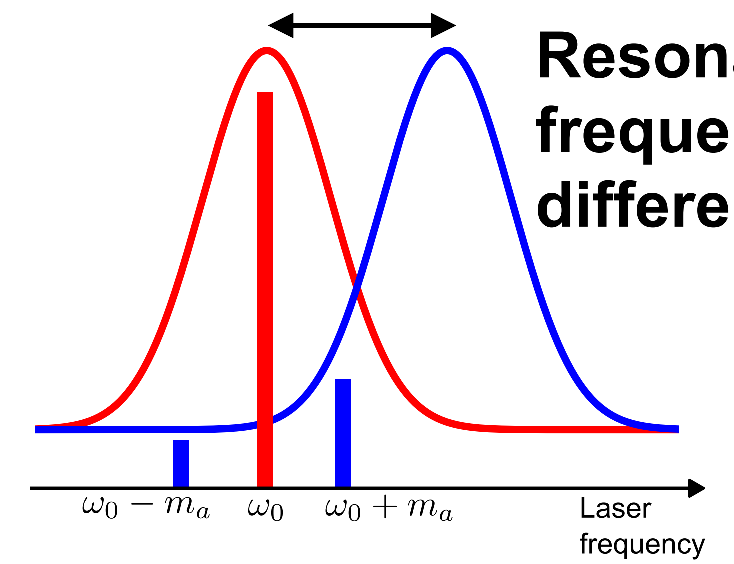


Issue: Simultaneous resonance

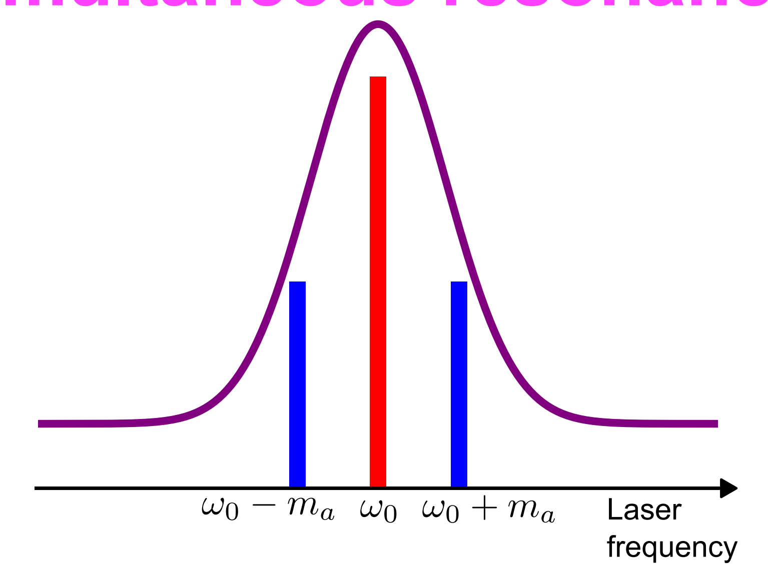
Reflection phase difference on the mirrors

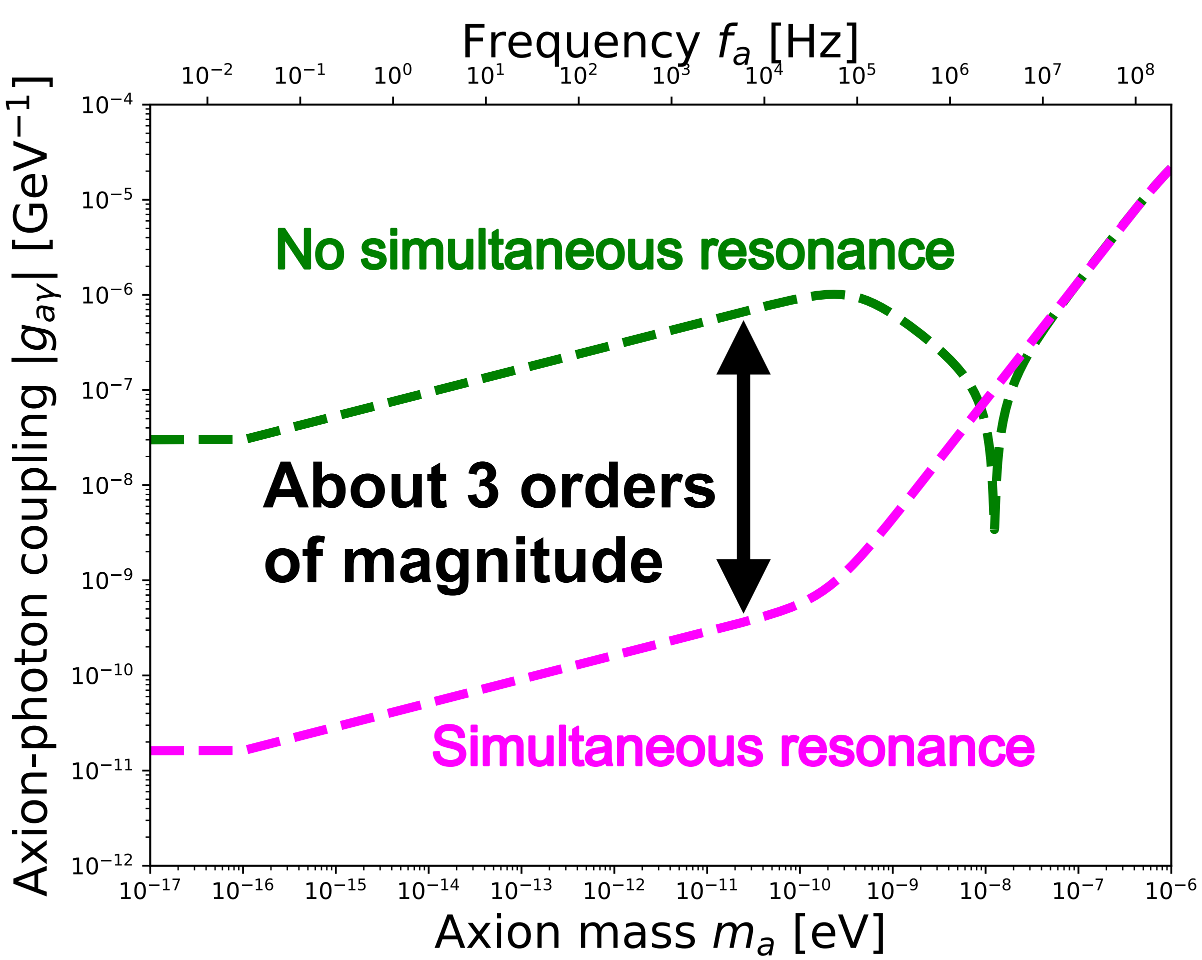


No simultaneous resonance



Simultaneous resonance

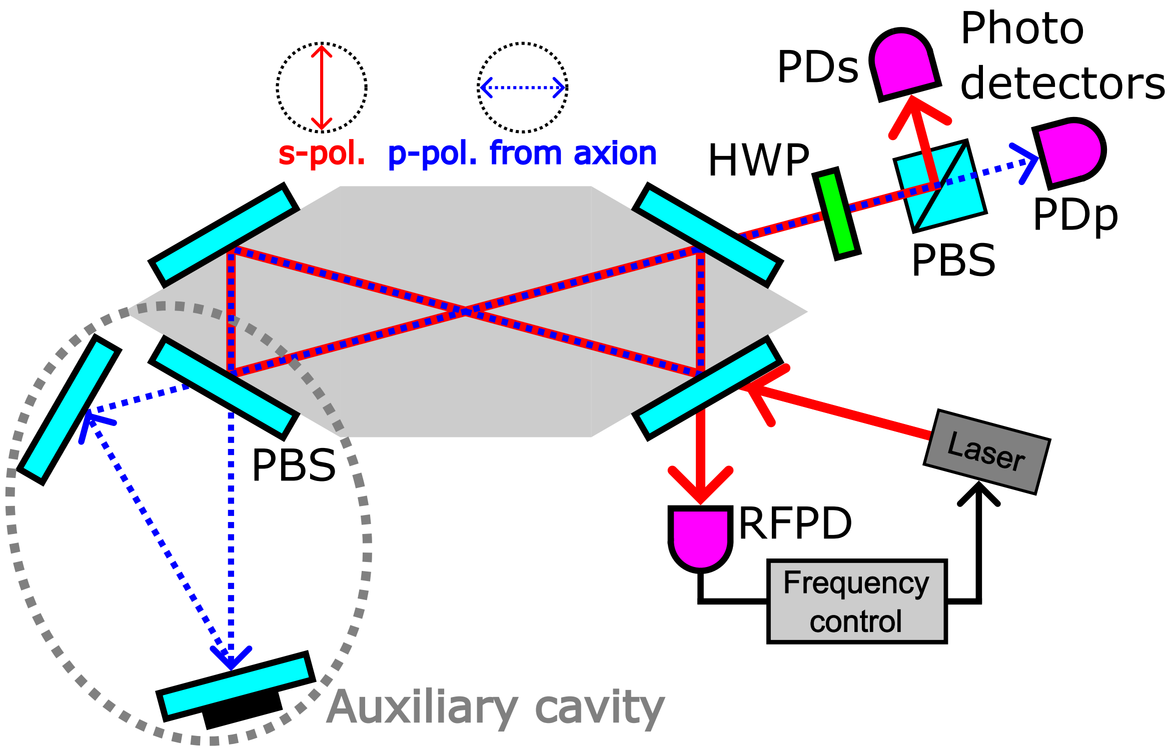




Simultaneous resonance is necessary to conduct a sensitive broadband axion search

How to achieve simultaneous resonance

DANCE with an auxiliary cavity



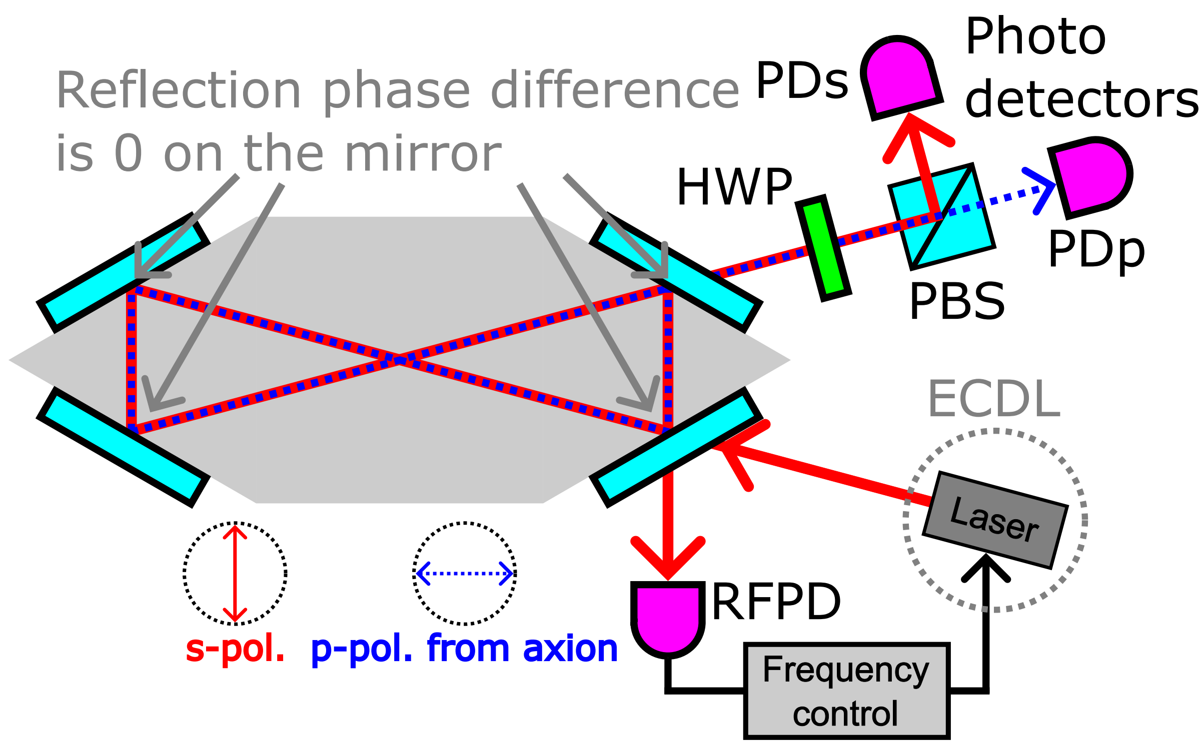
Advantage

Control the reflection phase difference between s-pol. and p-pol. for simultaneous resonance easily

Disadvantage

The optical loss on the polarizing beam splitter (PBS) between a bow-tie ring cavity and an auxiliary cavity degrades the sensitive to axion

DANCE with an ECDL



Advantage

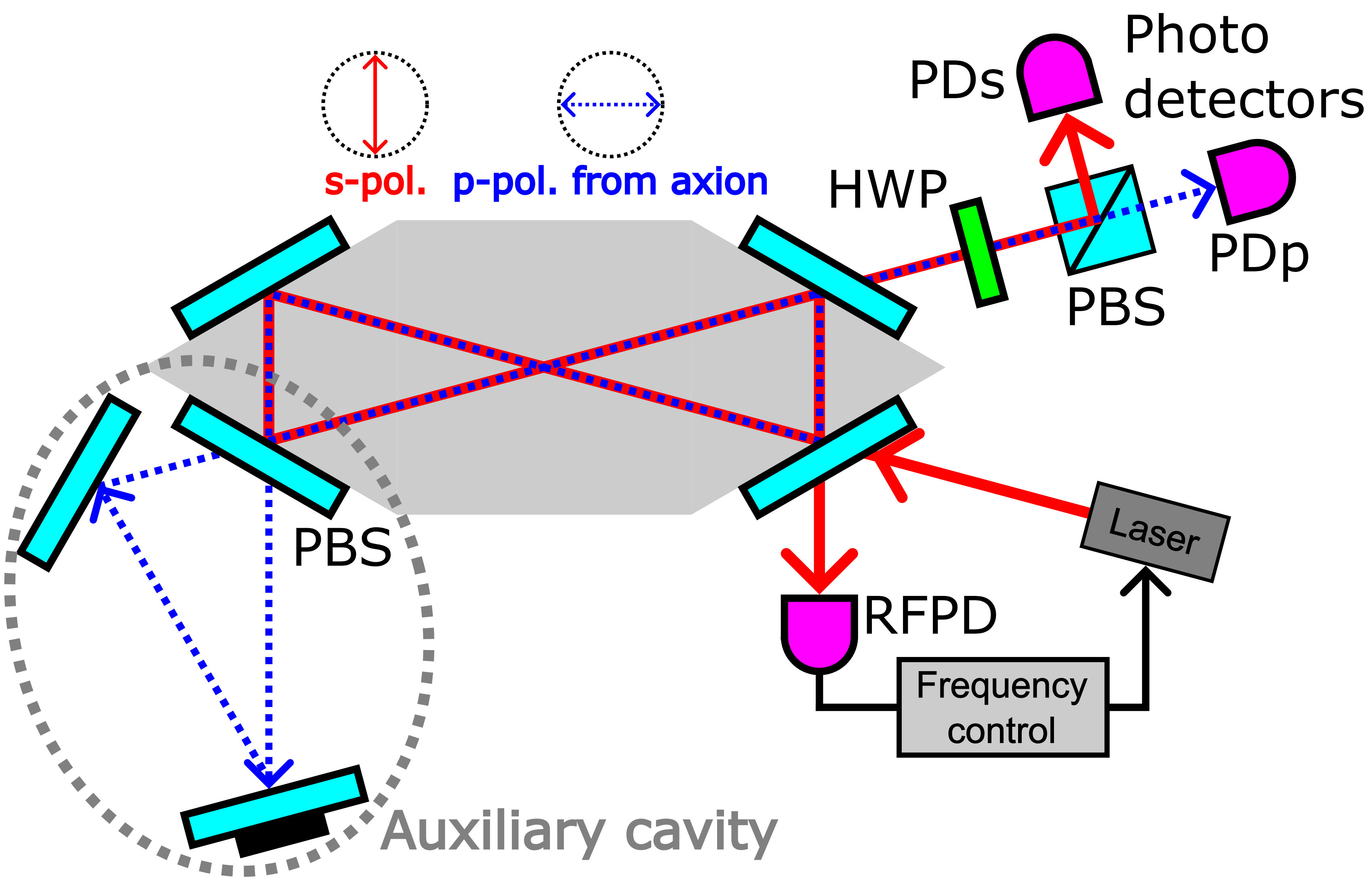
Achieve simultaneous resonance without an auxiliary cavity

Disadvantage

- Difficult to conduct mirror coating to cancel the reflection phase difference between s-pol. and p-pol.
- Need to use stable wavelength tunable laser

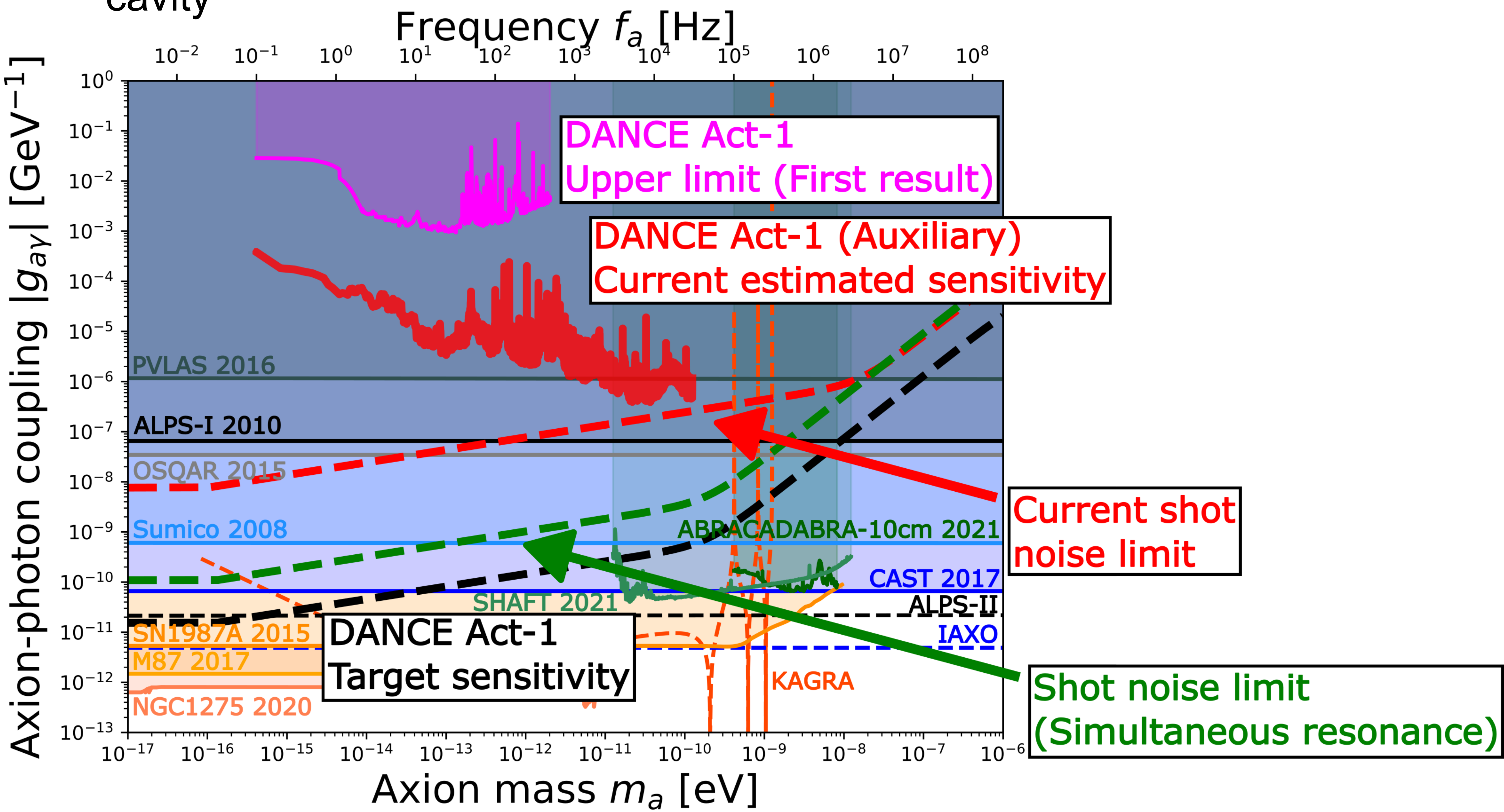
Simultaneous resonance with an auxiliary cavity

- Achieved simultaneous resonance in November 2021 by adding an auxiliary cavity to compensate for the reflection phase difference between s-pol. and p-pol.
- p-pol. is resonant in an auxiliary cavity by tuning PZT



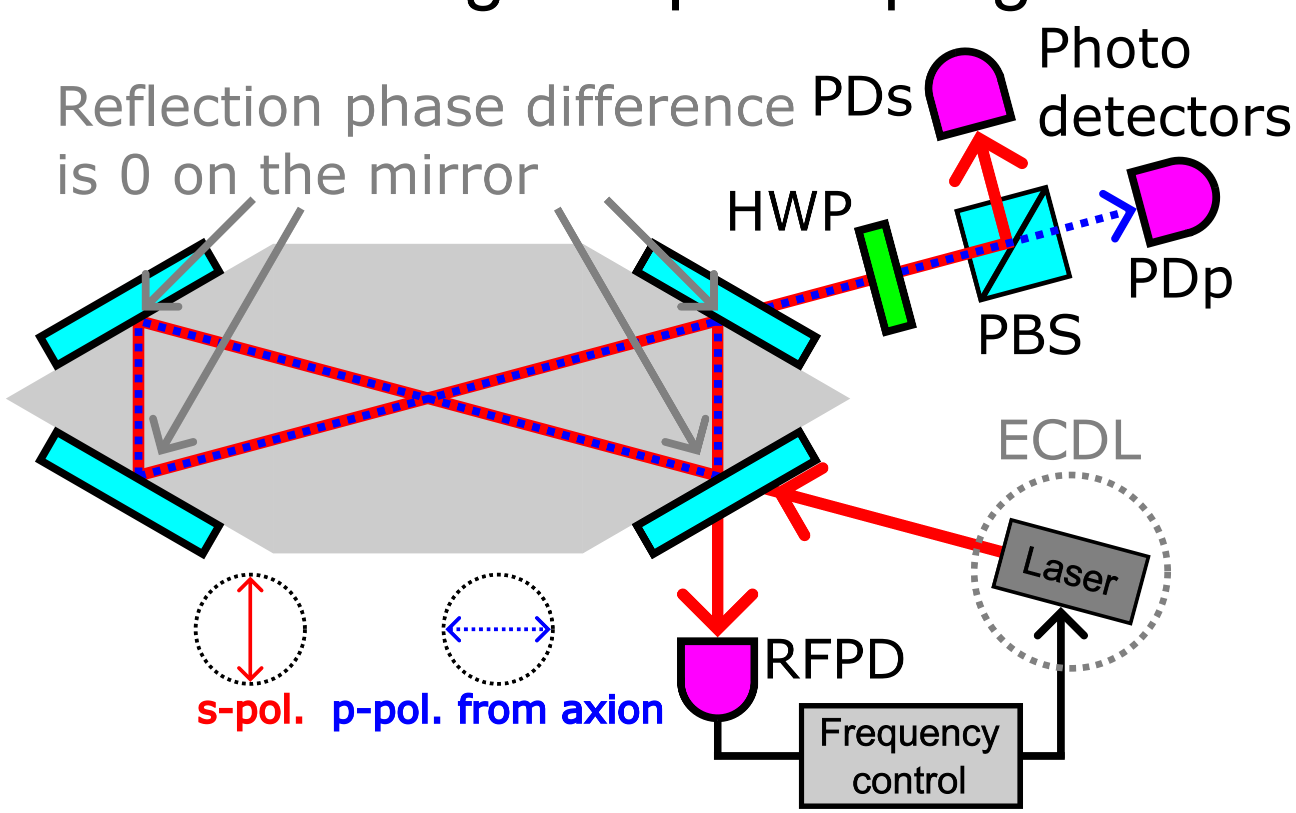
Simultaneous resonance with an auxiliary cavity

- Improved by more than 2 orders of magnitude
- Need to reduce the optical loss between a main cavity and an auxiliary cavity

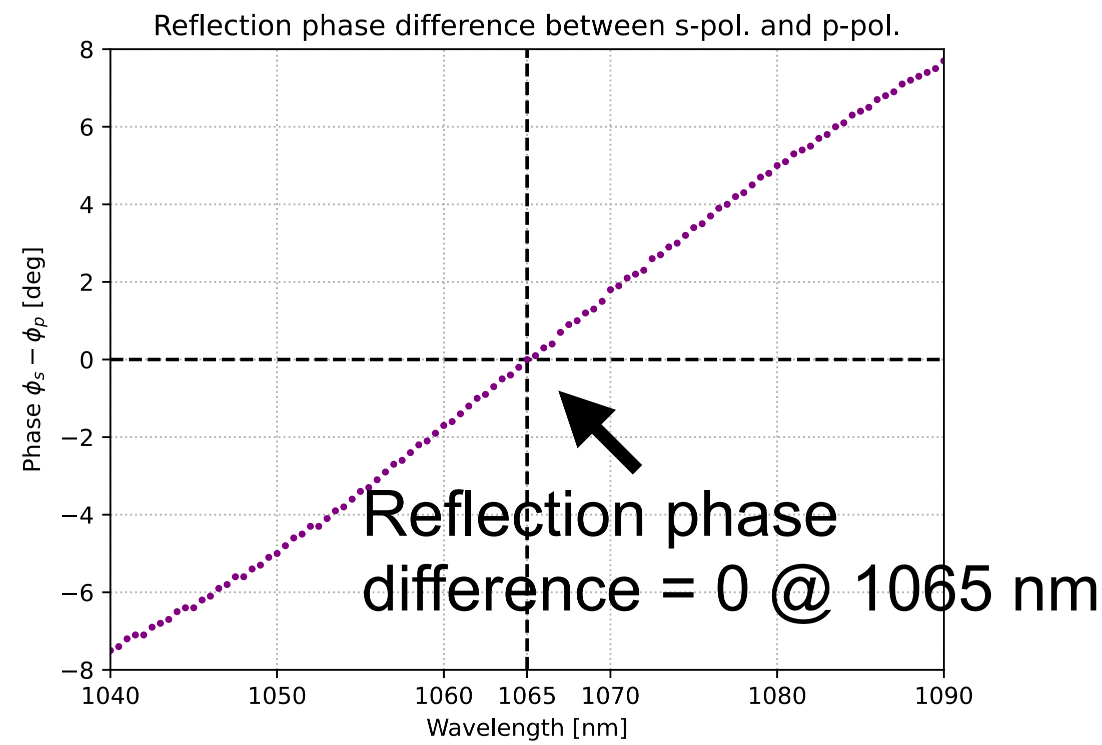


Simultaneous resonance with an ECDL

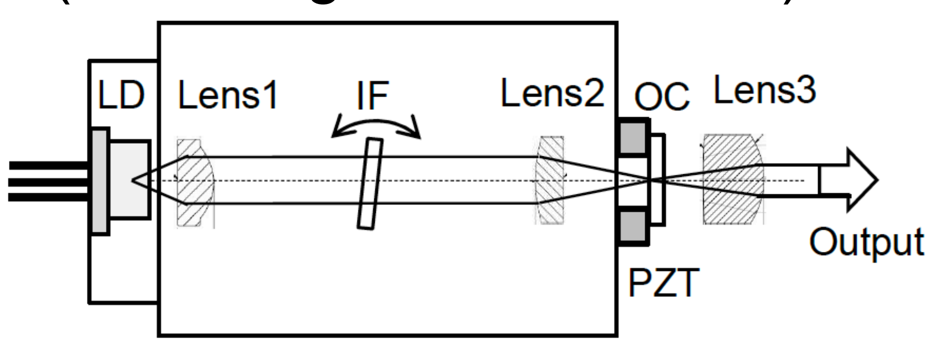
- Mirrors of reflection phase difference between s-pol.and p-pol. depends on laser wavelength
- Select the wavelength by finely adjusting the angle of the interference filter (IF)
- Constructing setup is in progress



Wavelength sensitive phase-shifting mirror



ECDL (wavelength tunable laser)

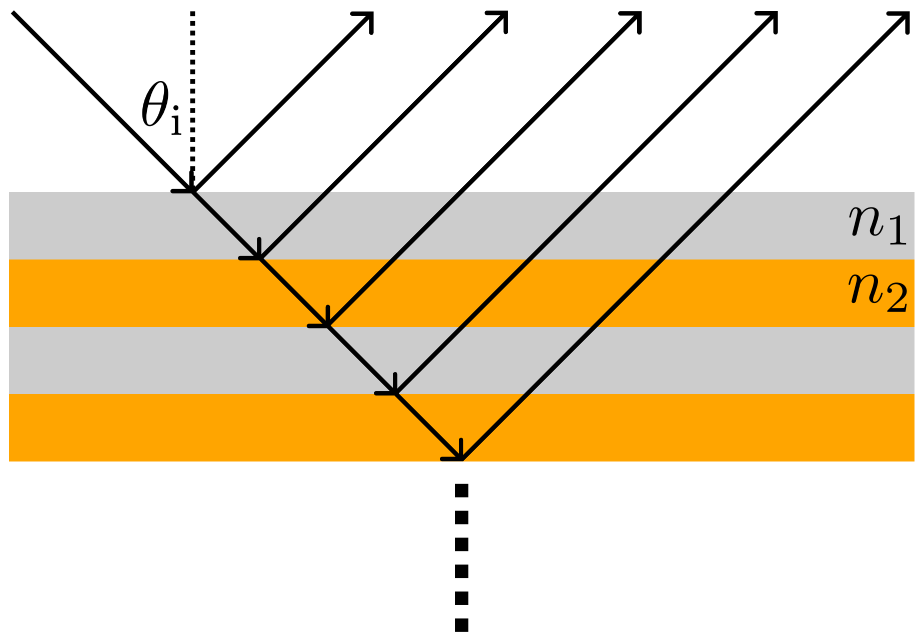


- Wavelength range: 1045 - 1068 nm
- FWHM: 200 kHz
- Output power: 20 - 50 mW

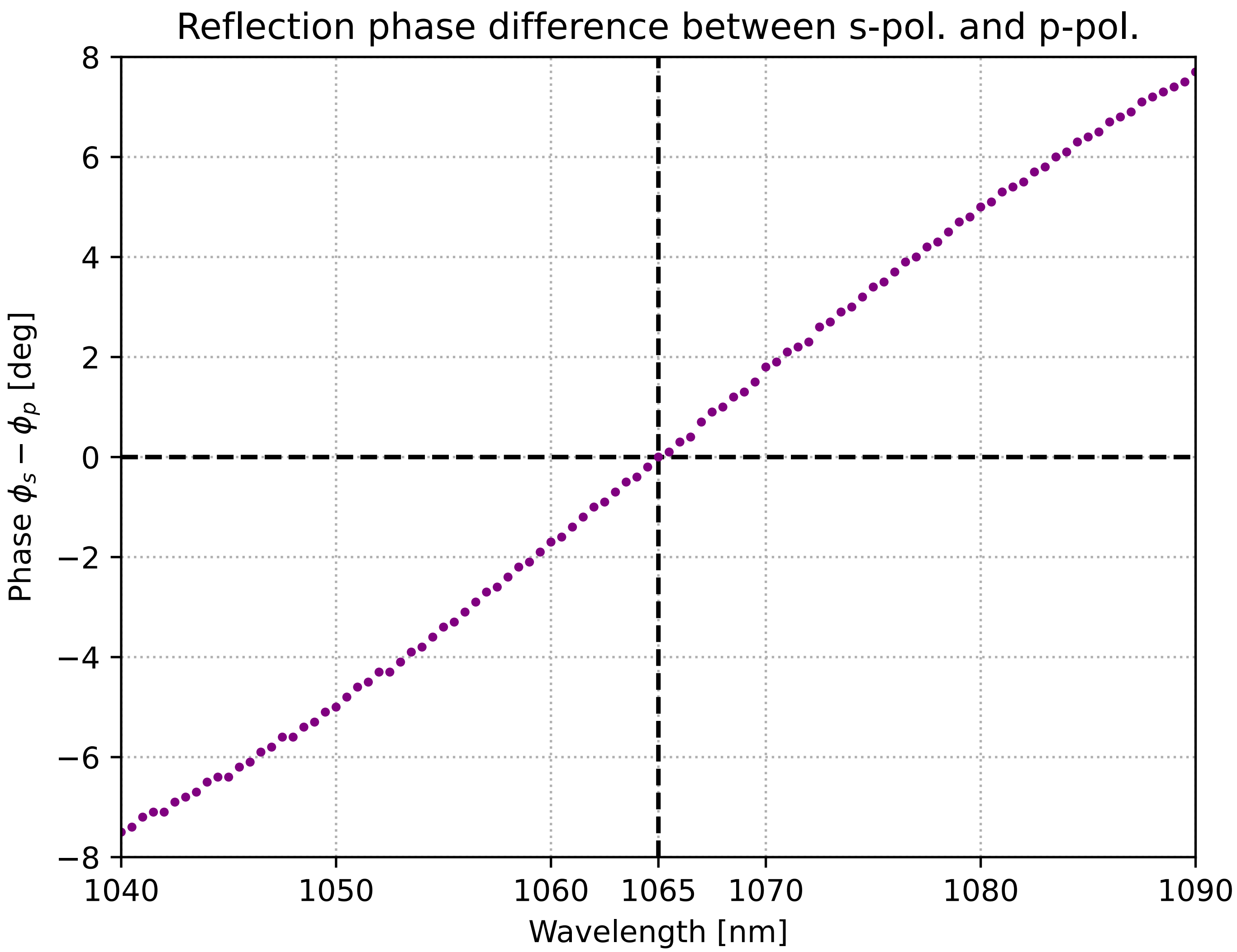
Wavelength sensitive phase-shifting mirror

Prepare wavelength sensitive phase-shifting mirror by dielectric multilayer film coating

Dielectric multilayer film coating

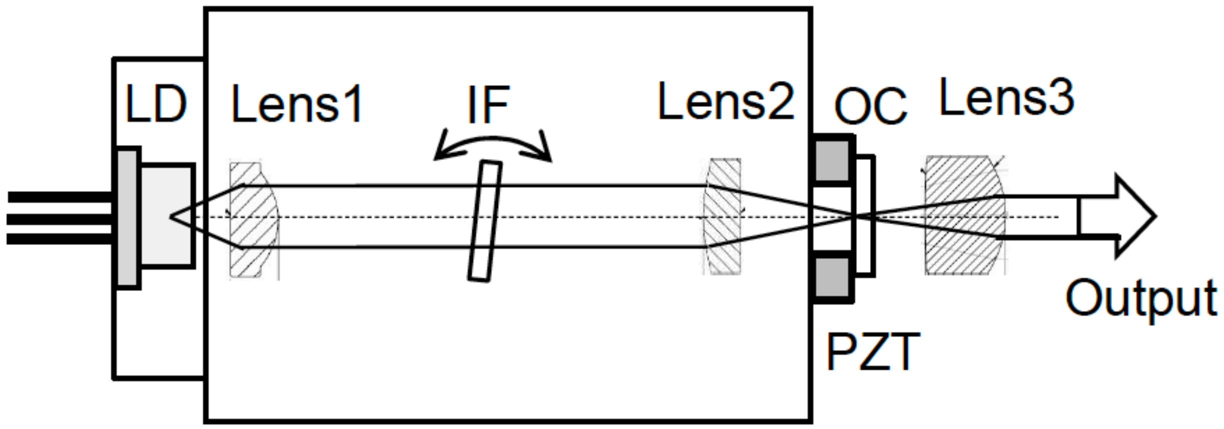


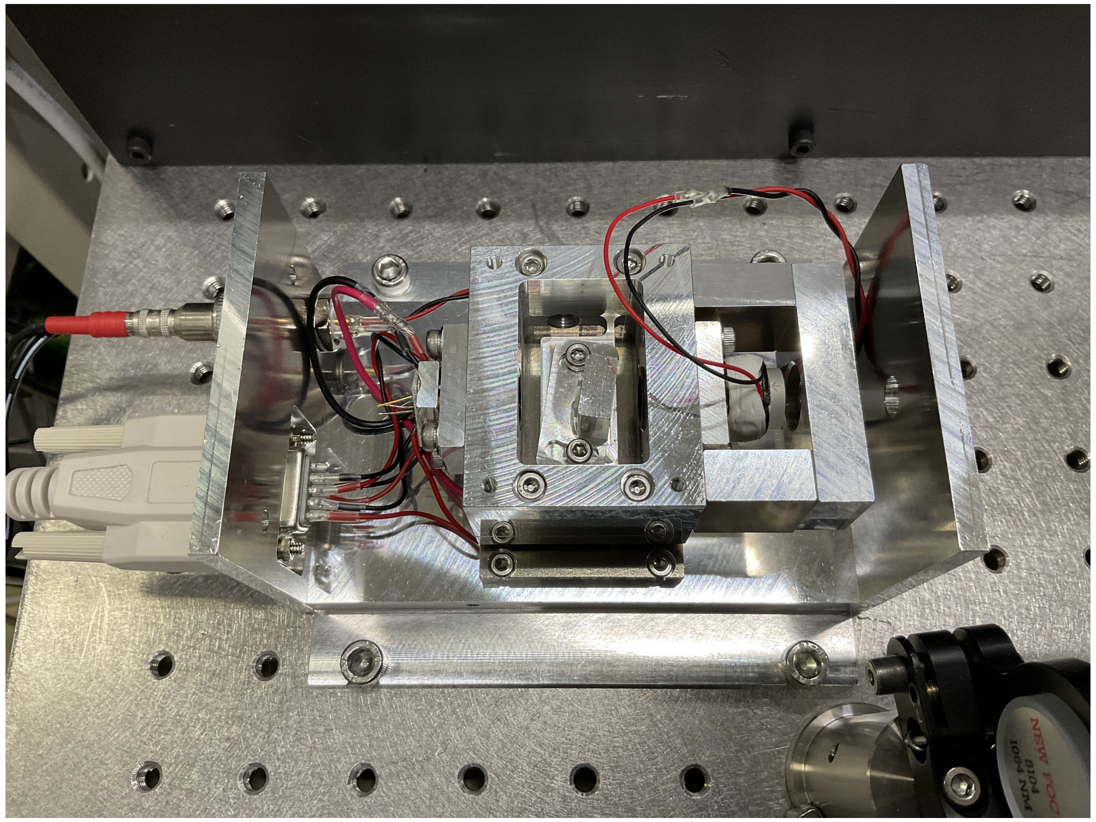
- Realize reflection phase difference continuously
- Realize high reflection by stacking low and high refractive index material alternately



Wavelength dependence of reflection phase difference between s- and p-pol. (Layertec inc.)

Wavelength tunable laser (Nakagawa ECDL)





External cavity diode laser (ECDL)

- Wavelength range: 1045 - 1068 nm
- FWHM: 200 kHz
- Output power: 20 - 50 mW

<u>Characteristics</u>

- Amplify output by constructing cavity between LD and OC
- Closed structure ⇒ Resistant to acoustic noise and vibrations
- Select wavelength by finely adjusting the angle of the Interference Filter (IF)
  ⇒ The optical axis remains because the structure has a transparent design

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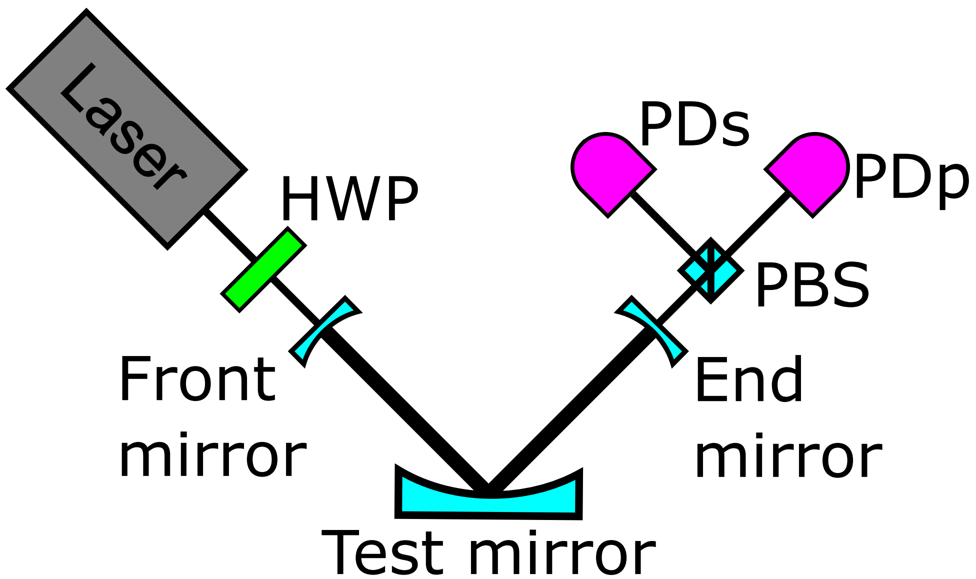
Measurement of reflection phase difference

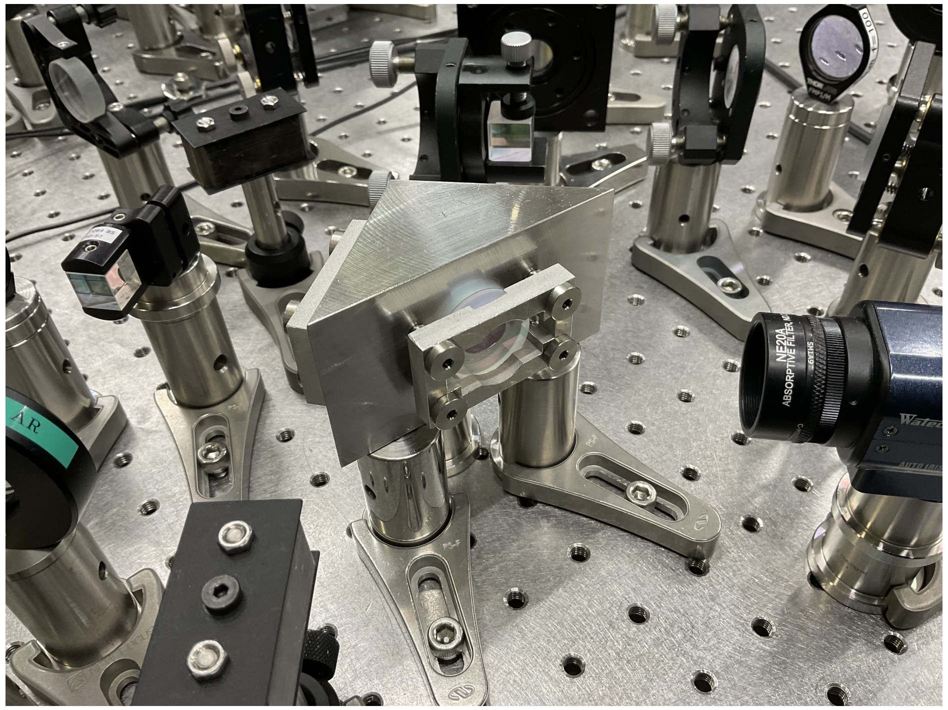
Establishment of simultaneous resonance with a folded cavity

① Reflection phase difference between s-pol. and p-pol. depends on wavelength

② Time drift of the reflection phase difference between s-pol. and p-pol.

⟹ Difficult to conduct an accurately sensitive axion search





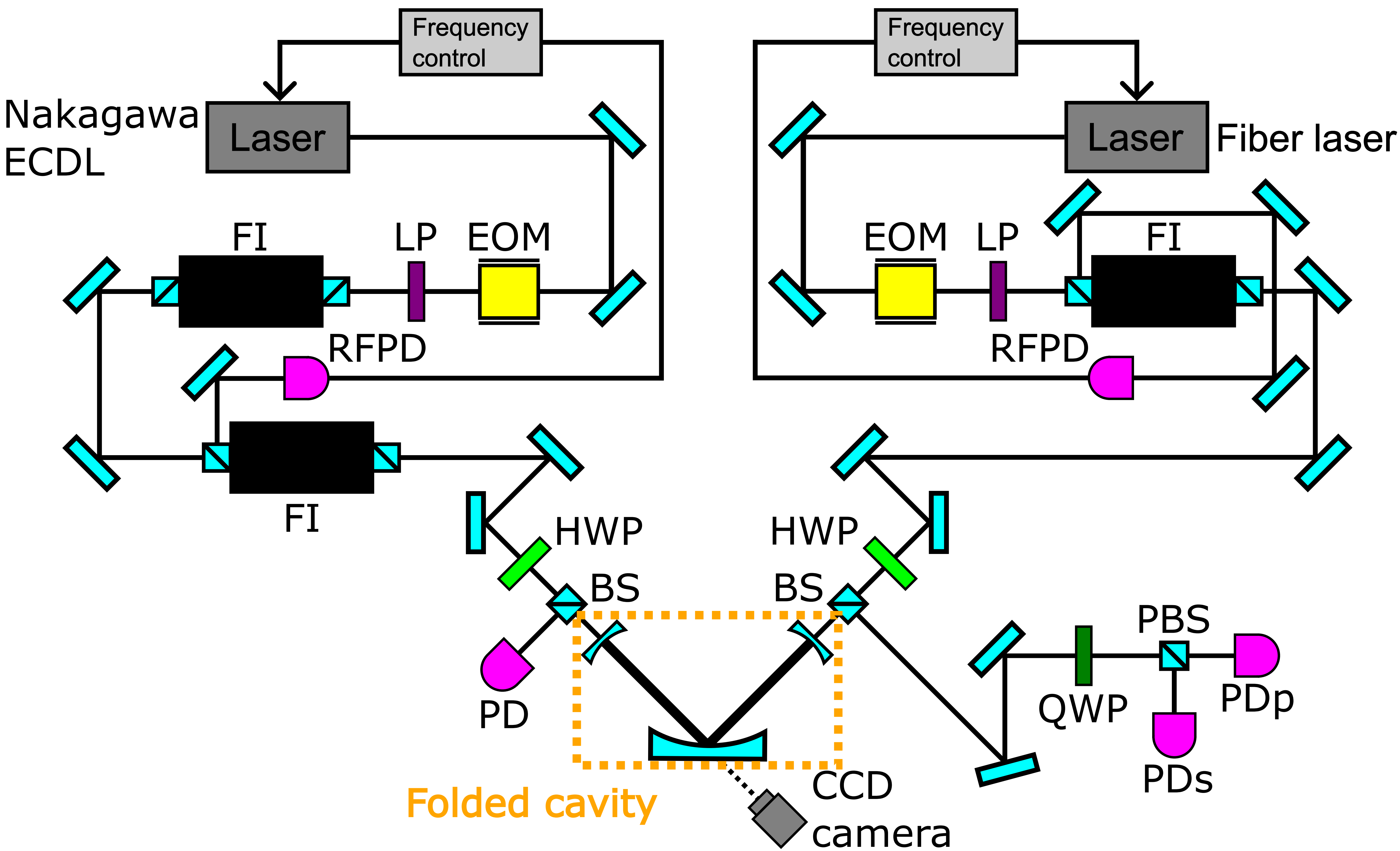
$\Delta\phi$: reflection phase difference between s-pol. and p-pol.

<u>Requirement for simultaneous resonance</u>

$$\Delta\phi \leq 0.015 \text{ deg}$$

Mirror	Reflectivity	CC[mm]
Front	99%	50
End	99%	50
Test	s-pol.: 99.99%, p-pol.: 99.97%	1000

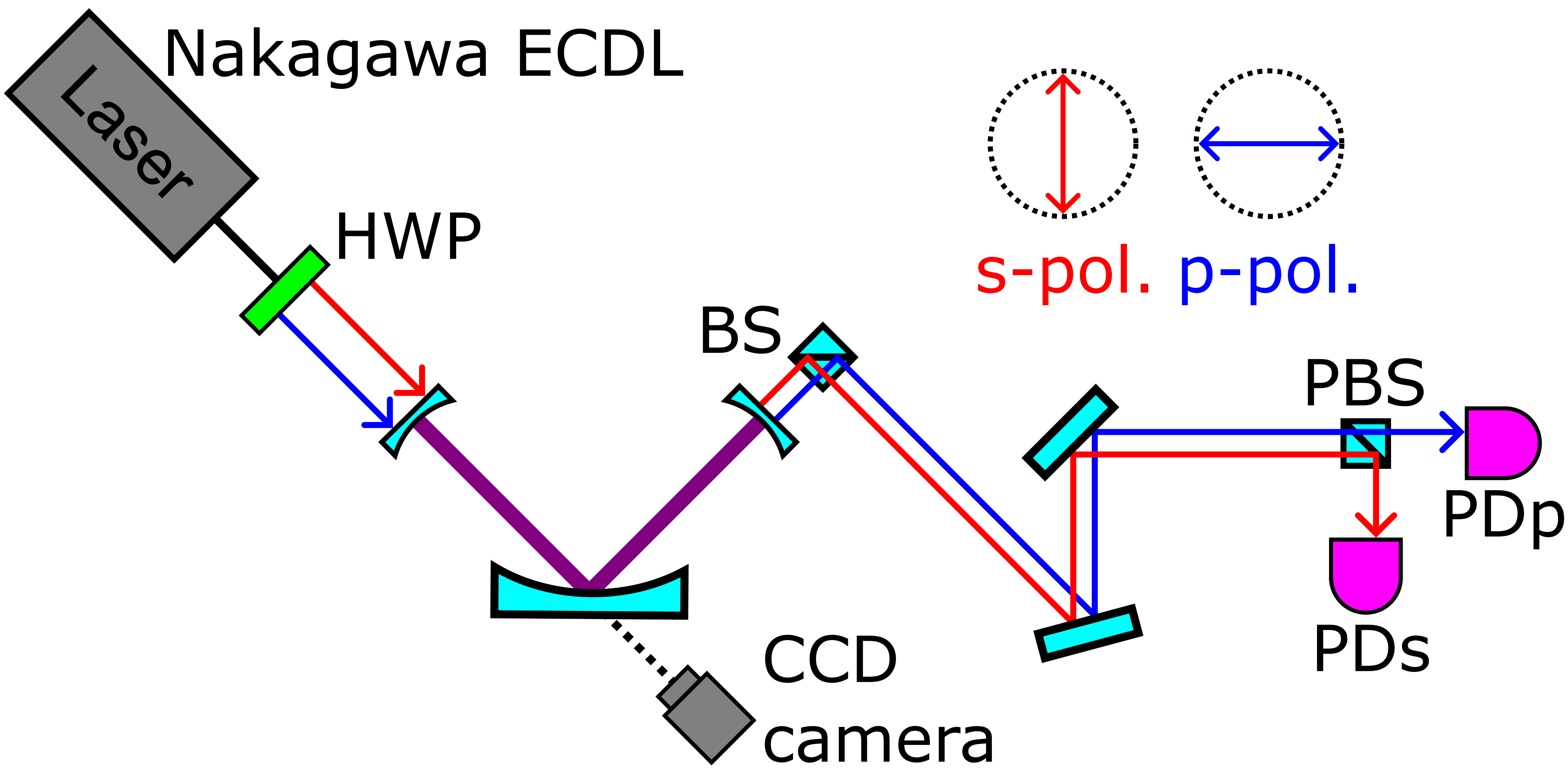
Overview of experimental setup



① Wavelength vs reflection phase difference

Reflection phase difference between s- and p-pol. per mirror

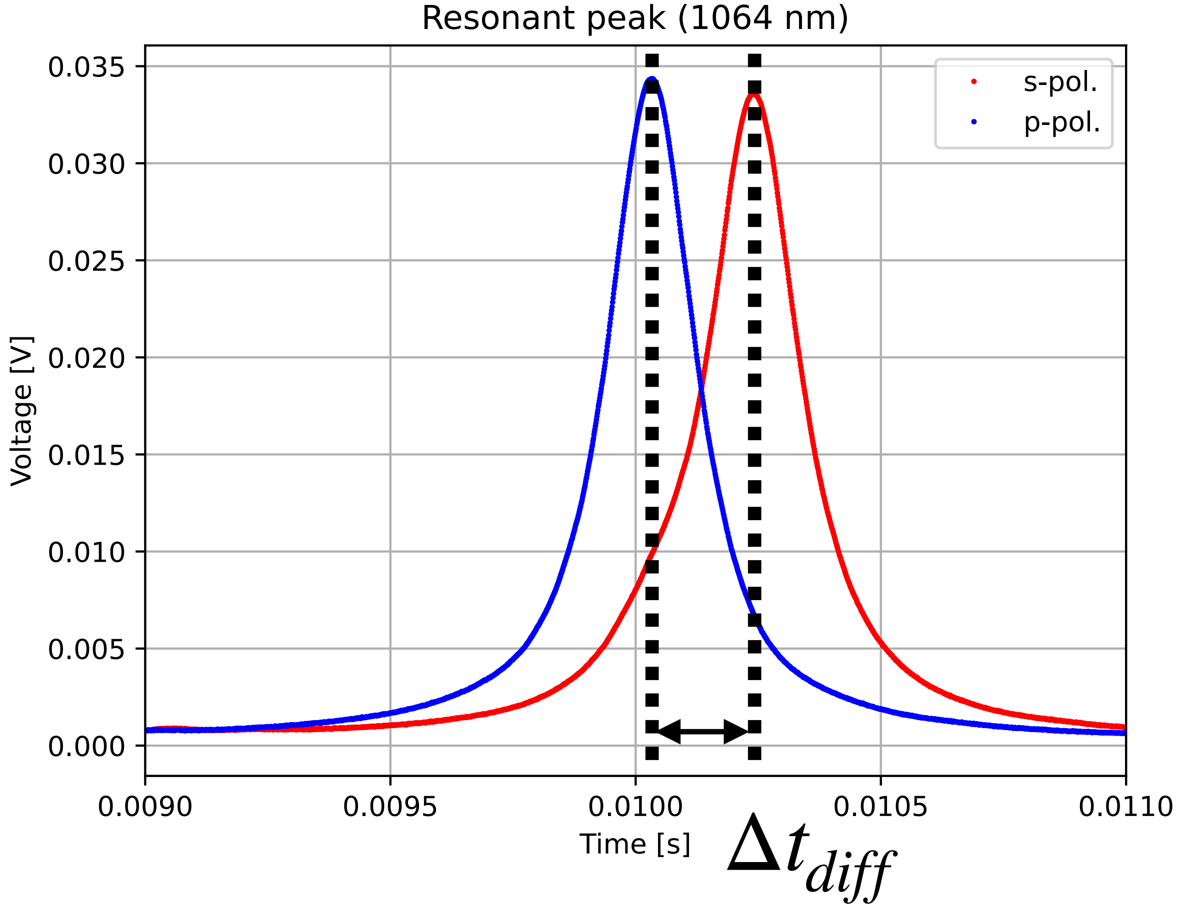
- Selected the wavelength from 1064 nm to 1068 nm in 0.5 nm increments and measured 10 times at each wavelength
- Obtained transmitted light by tuning laser frequency with PZT in ECDL



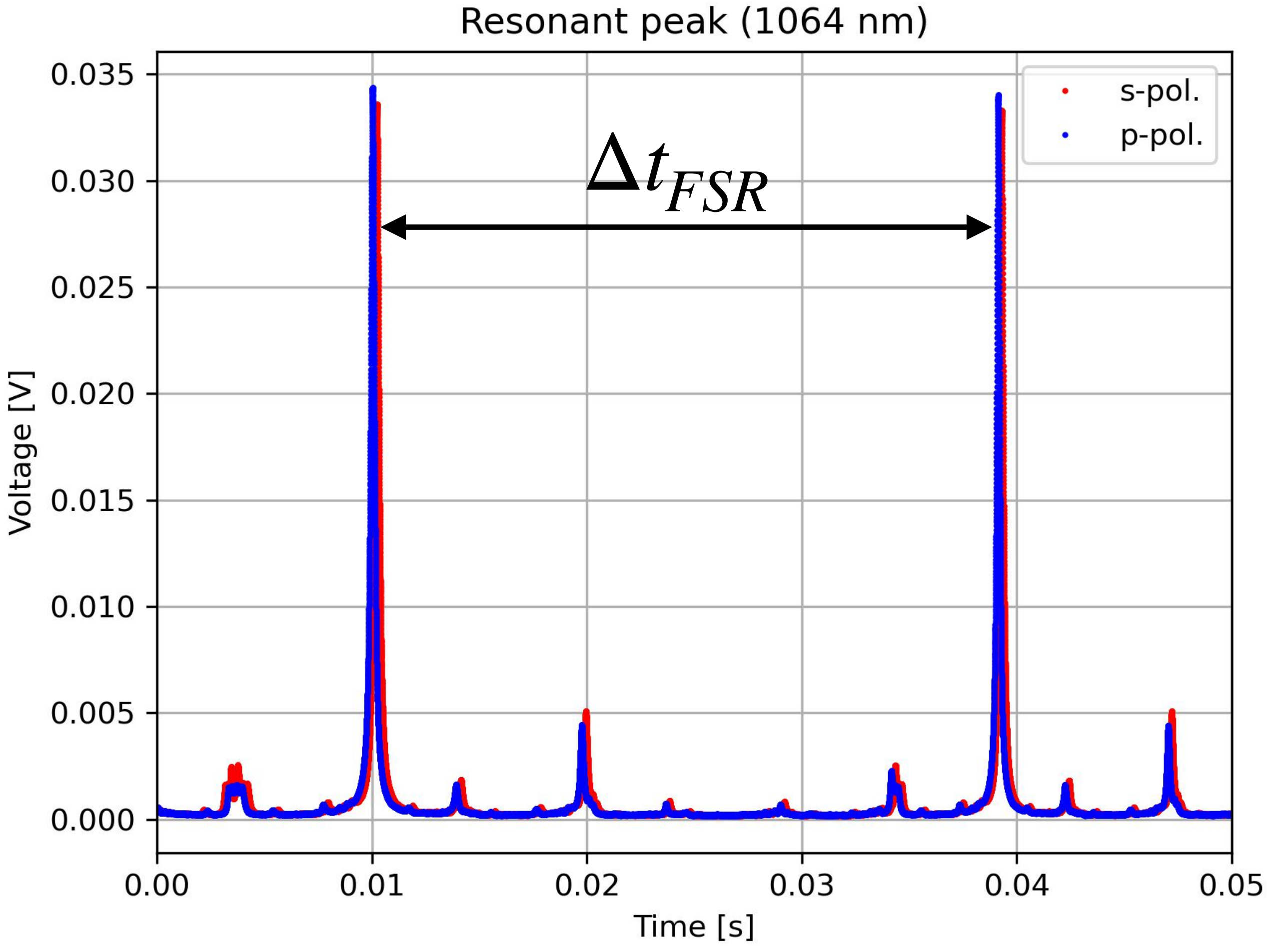
① Wavelength vs reflection phase difference

Reflection phase difference per mirror

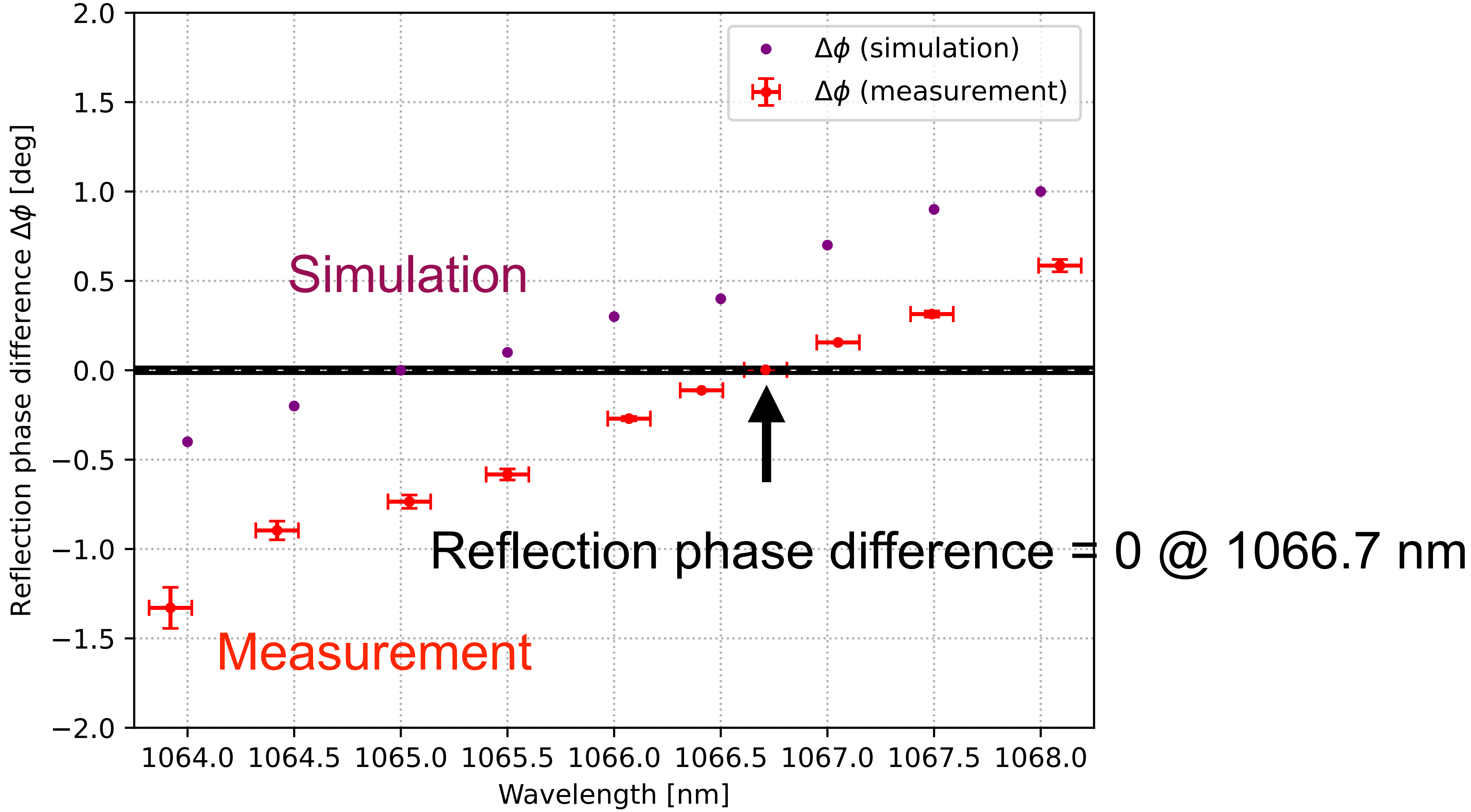
$$\Delta\phi = \frac{\Delta t_{\rm diff}}{\Delta t_{\rm FSR}} \times 180\ {\rm deg}$$



Resonant frequency difference

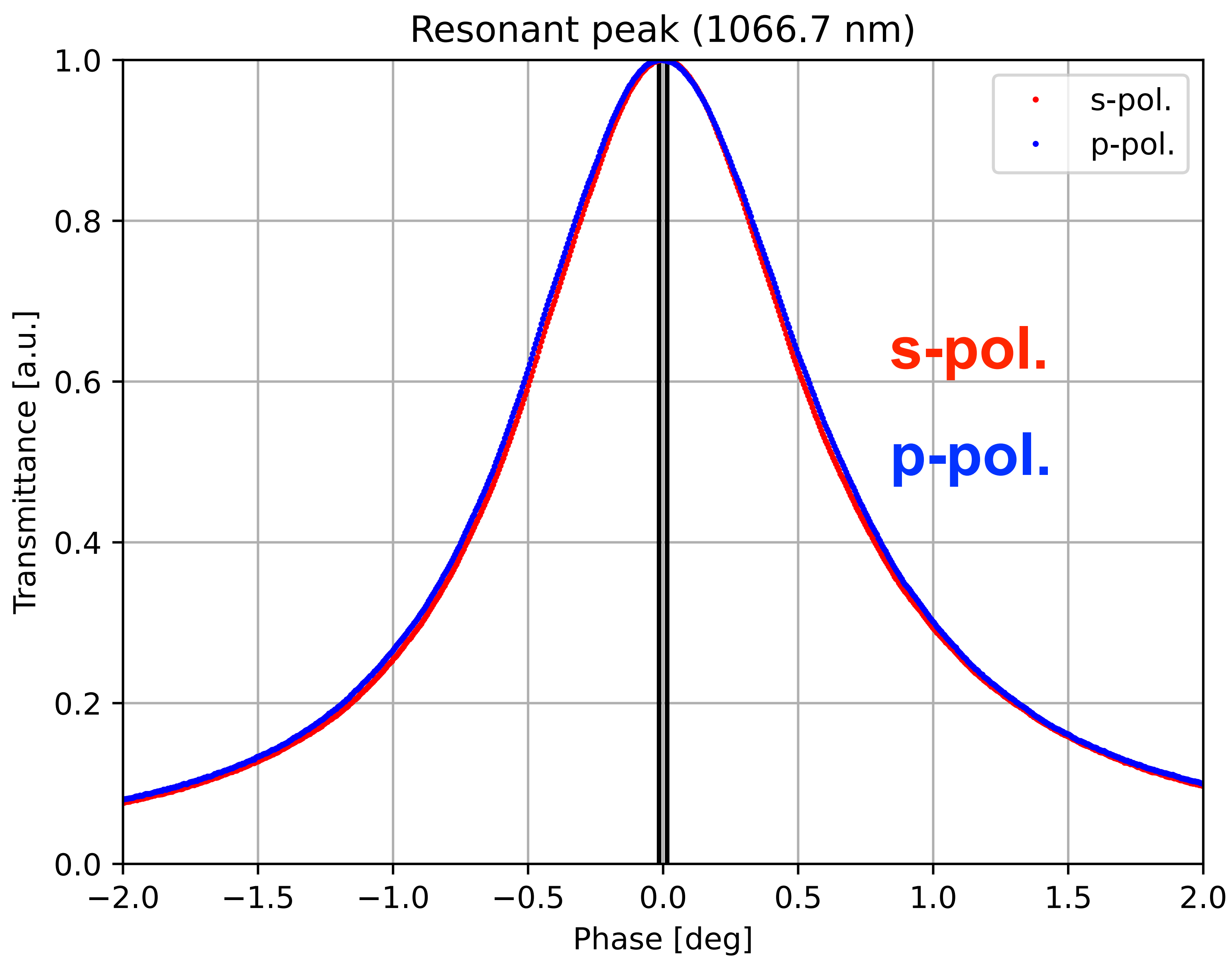


① Wavelength vs reflection phase difference



Measured reflection phase difference utilizing wavelength tunable laser
⇒ Reflection phase difference is 0 @ 1066.7 nm

① Wavelength vs reflection phase difference



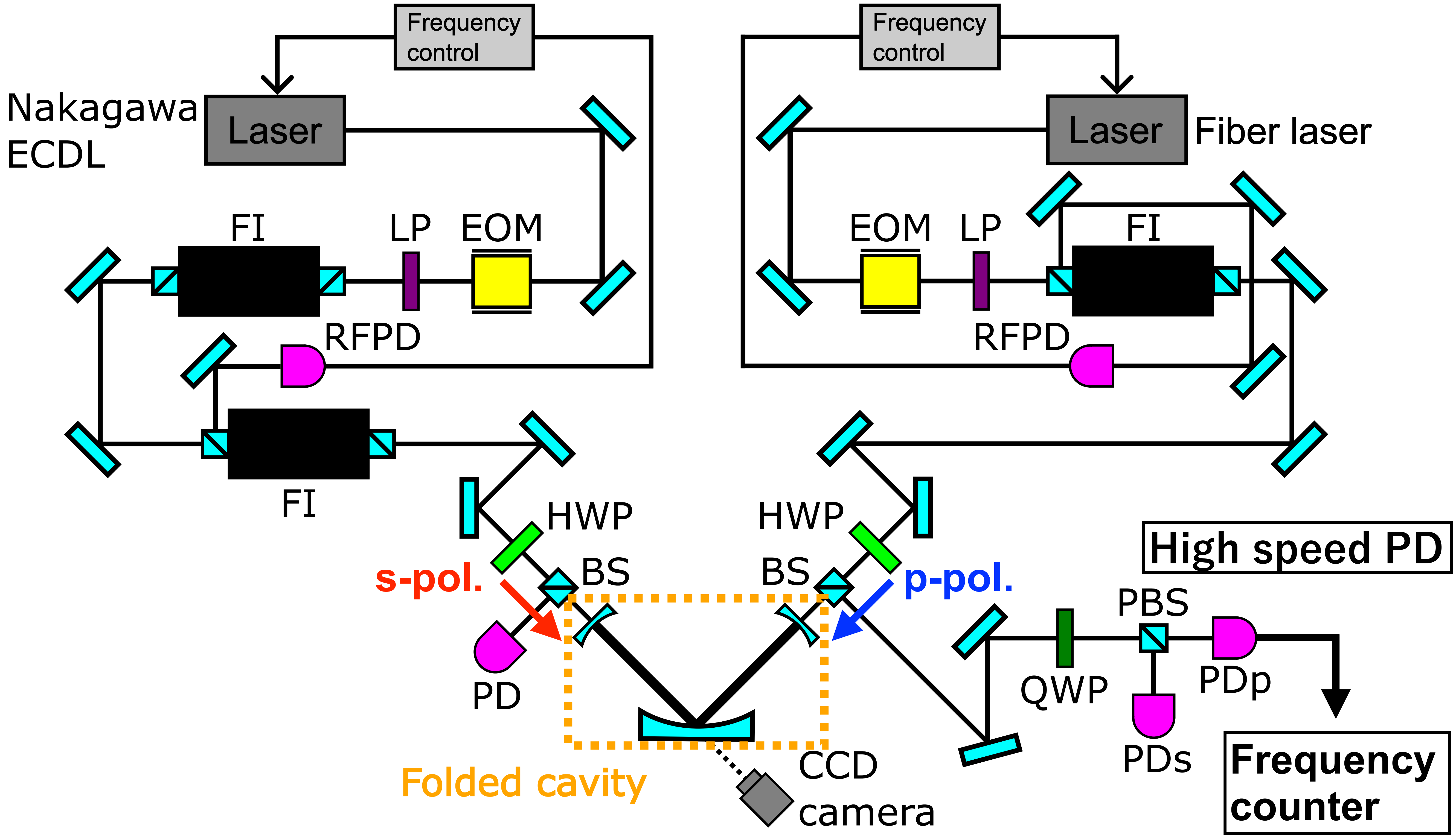
Measurement result $\Delta\phi = \phi_\mathrm{s} - \phi_\mathrm{p} = 0.002(1)\ \mathrm{deg}\ @1066.7\ \mathrm{nm}$

⟹ Satisfy requirement for simultaneous resonance: $\Delta\phi \leq 0.015\ \mathrm{deg}$

⟹ Obtained wavelength which achieves simultaneous resonance

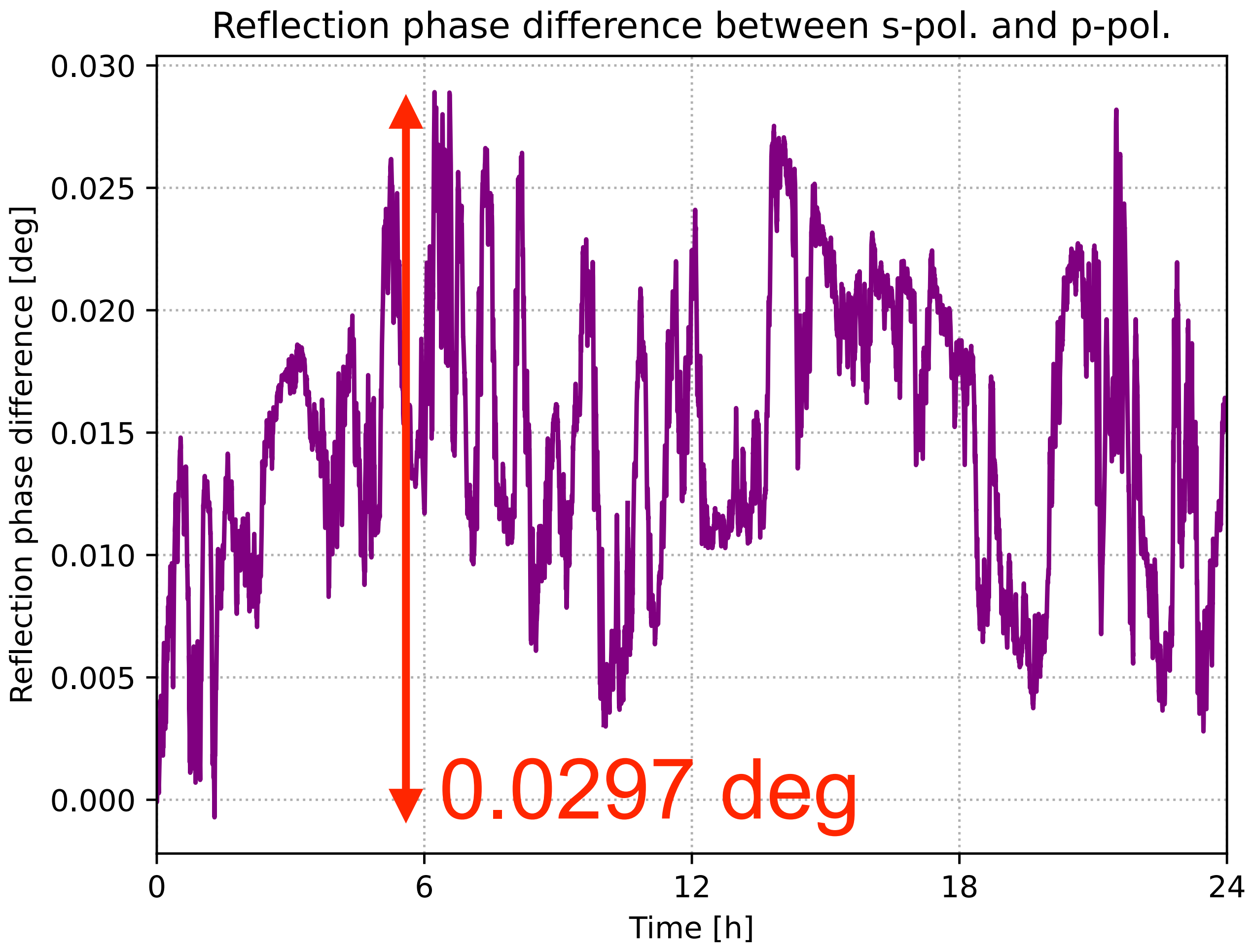
② Time drift of reflection phase difference

Time drift of reflection phase difference between s- and p-pol. (24 hours)
@ 1064 nm

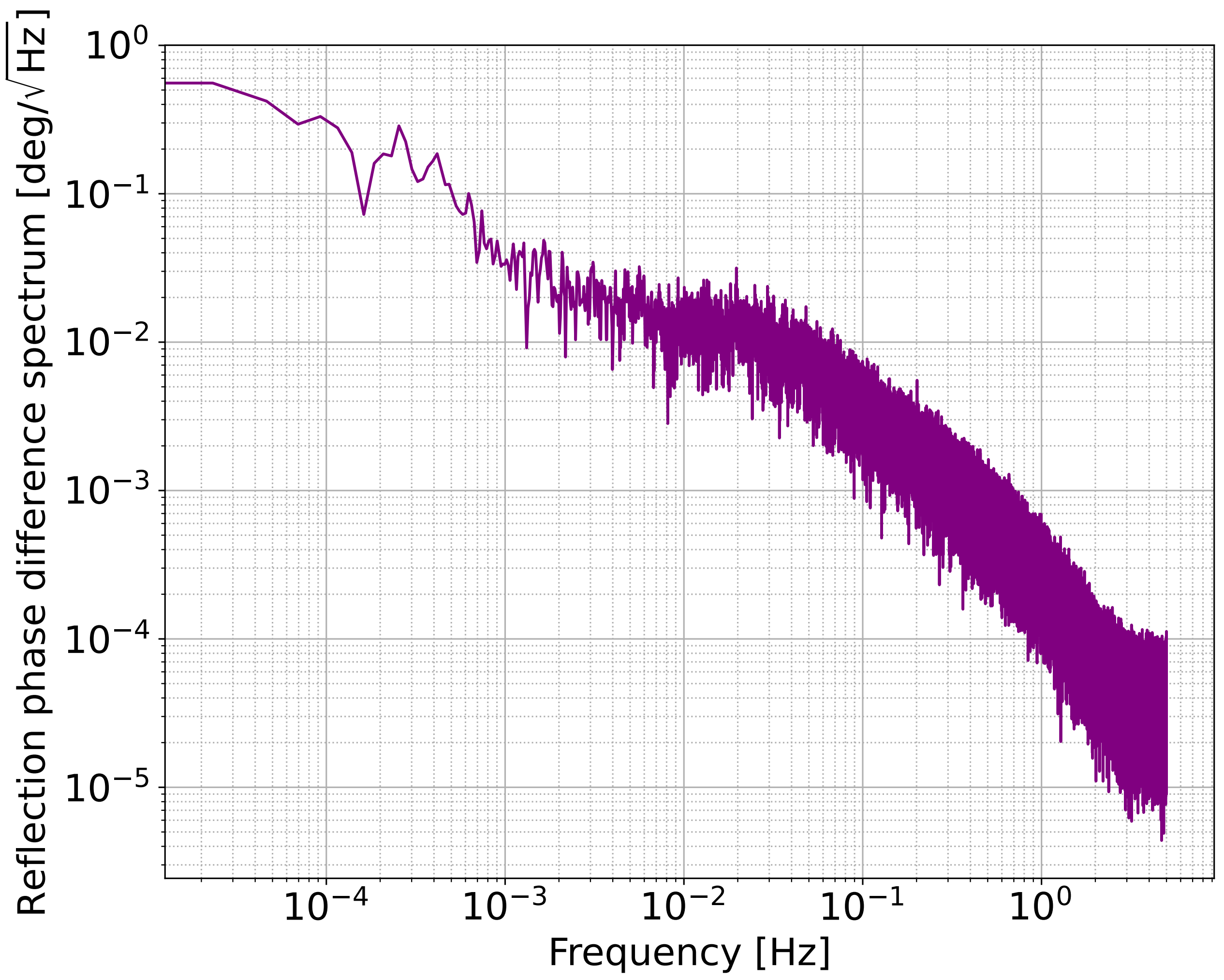


② Time drift of reflection phase difference

Time drift of reflection phase difference



Power spectrum



- Fluctuation range: 0.00 - 0.03 deg

⇒ Did not satisfy requirement for simultaneous resonance: $\Delta\phi \leq 0.015$ deg

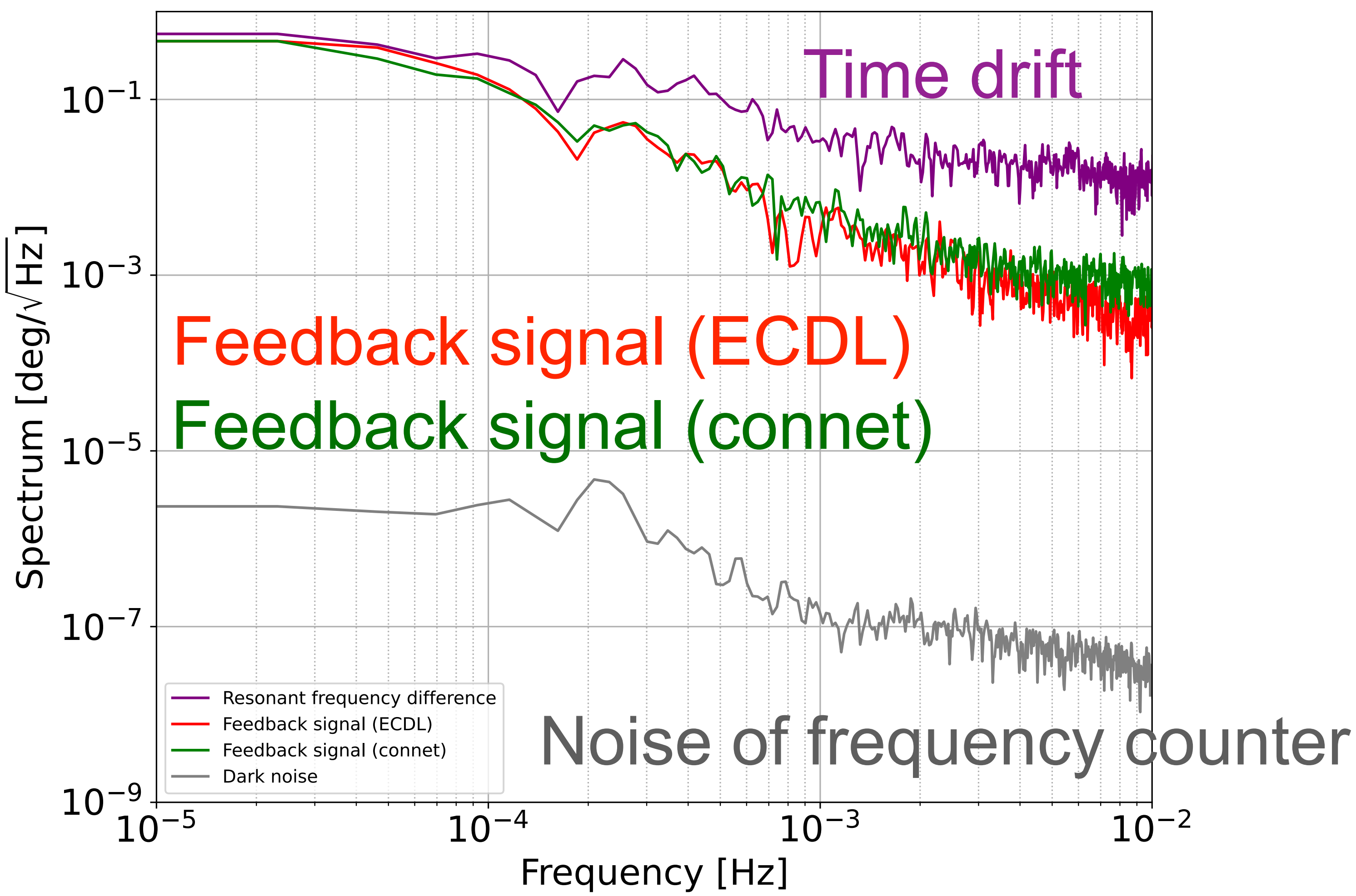
⇒ Investigate the cause of time drift

- Peak at around 2.5×10^{-4} Hz (1 hour)

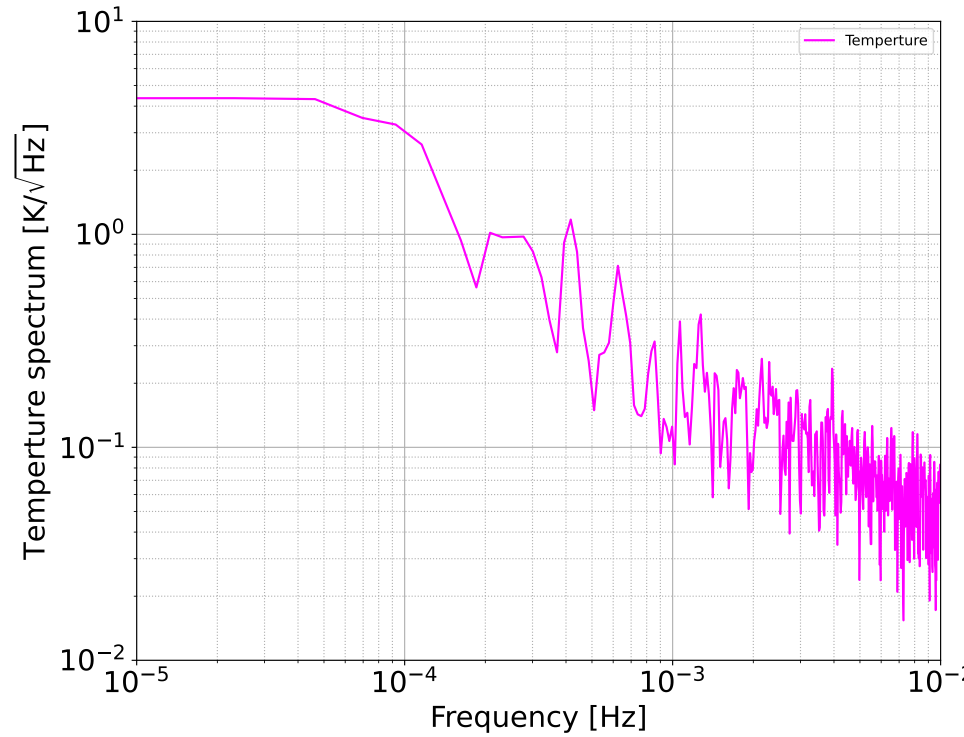
② Time drift of reflection phase difference

Feedback signal ⇒ Fluctuation of laser frequency

Temperature ⇒ Fluctuation of thickness of film

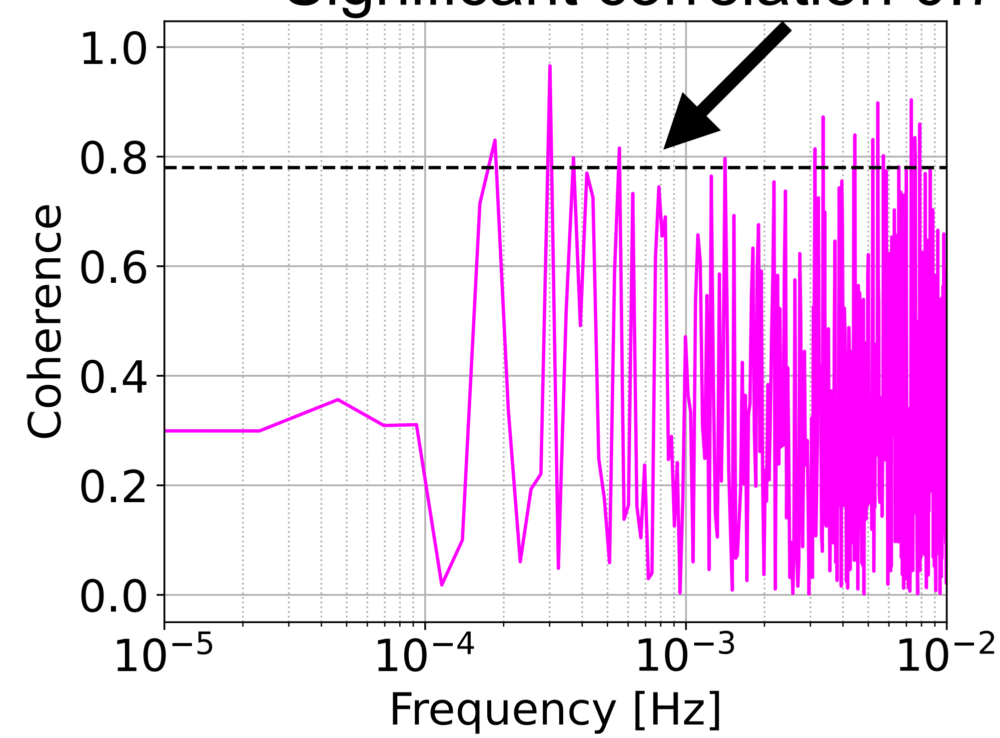


Temperature fluctuation



Coherence with temperature

Significant correlation 0.78



Comparison of each signal and time drift

⇒ Peak at around 2.5×10^{-4} Hz (1 hour)

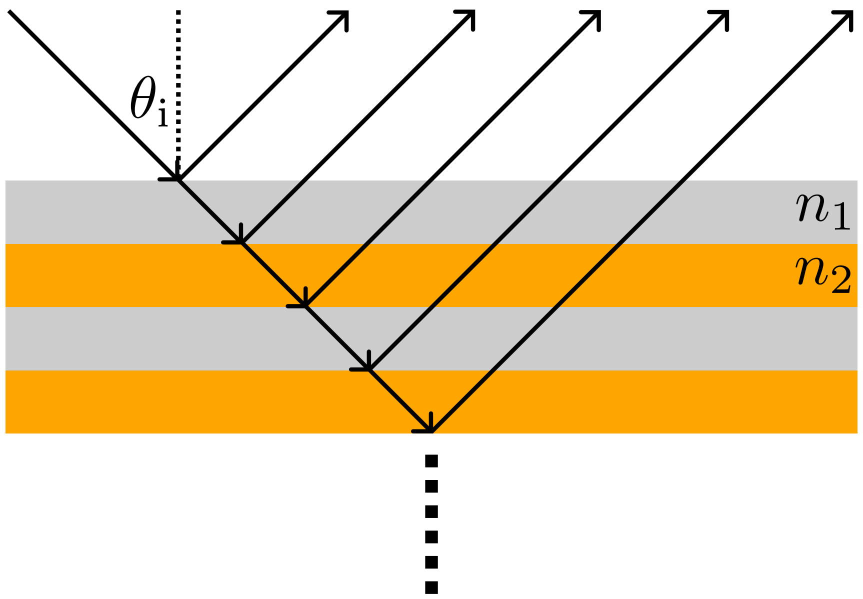
⇒ Possibility of coherence with some signals

② Time drift of reflection phase difference

Temperature fluctuation

⟹ Time drift of reflection phase difference

Dielectric multilayer coating

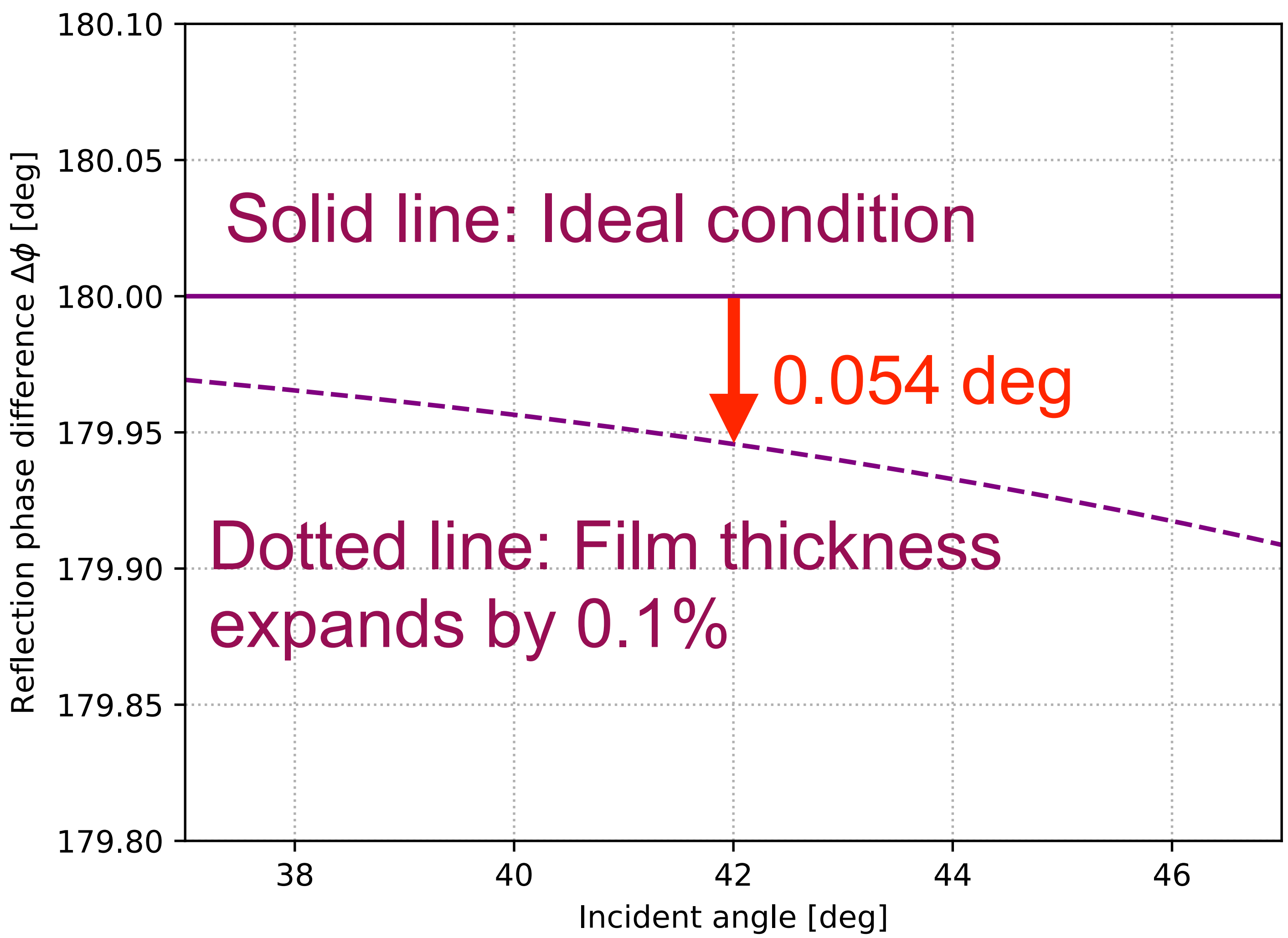


Refractive index

$$SiO_2 \ (n_1 = 1.44)$$

$$Ta_2O_5 \ (n_2 = 2.2)$$

20 layer is stacked



Temperature fluctuation leads to expand film thickness and change refractive index

⟹ Quantitative evaluation will be conducted in the future

Contents

Noise reduction for folded cavity experiment

Cavity lock is unstable at specific frequency

⇒ Adding an voltage with an offset circuit and shifting the resonance point to around 12MHz, the fluctuation of PDH signal disappeared.

Phase modulation frequency from EOM: 15MHz

Resonant frequency difference: 7MHz

⇒ Beat frequency is 14MHz because of two reflections

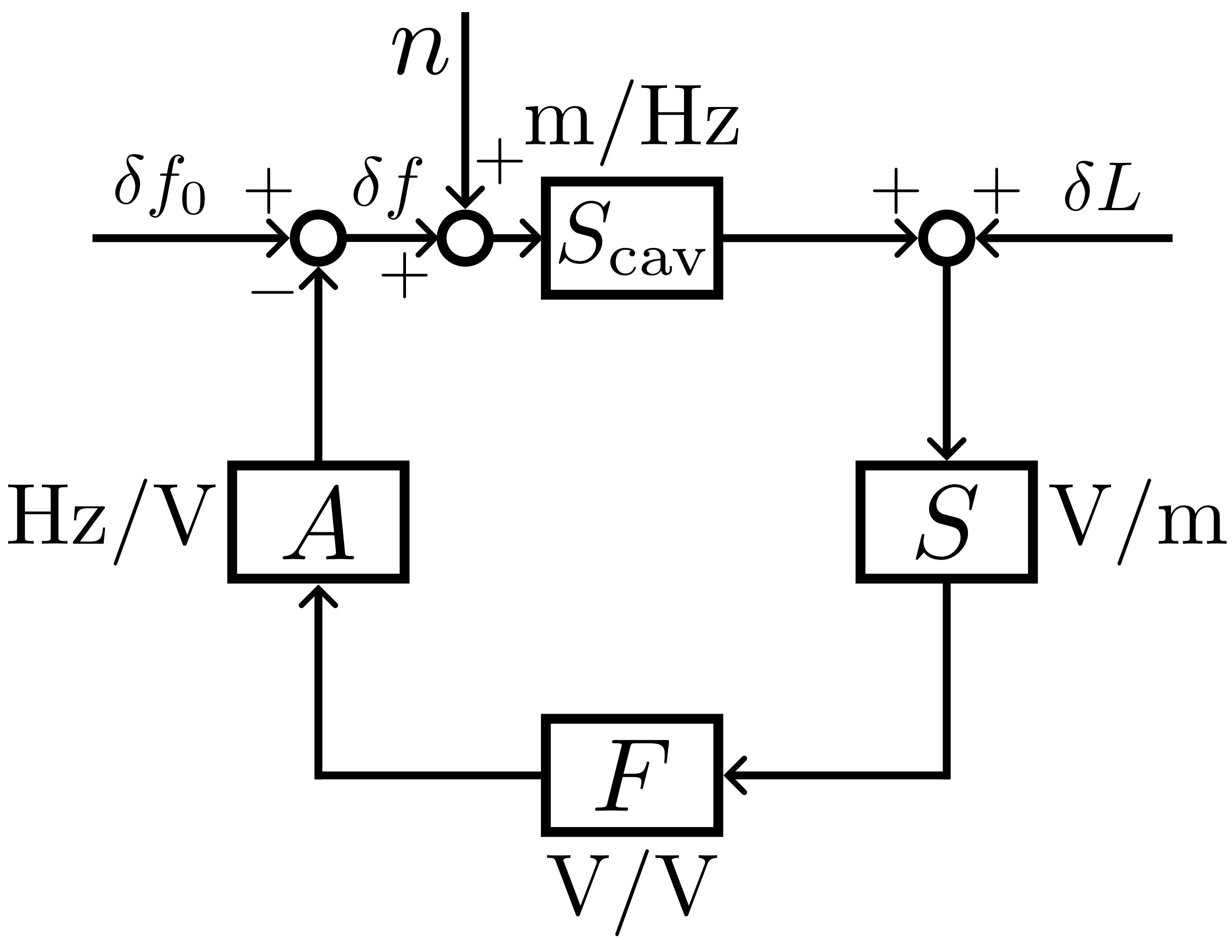
<u>Possible cause of the problem</u>

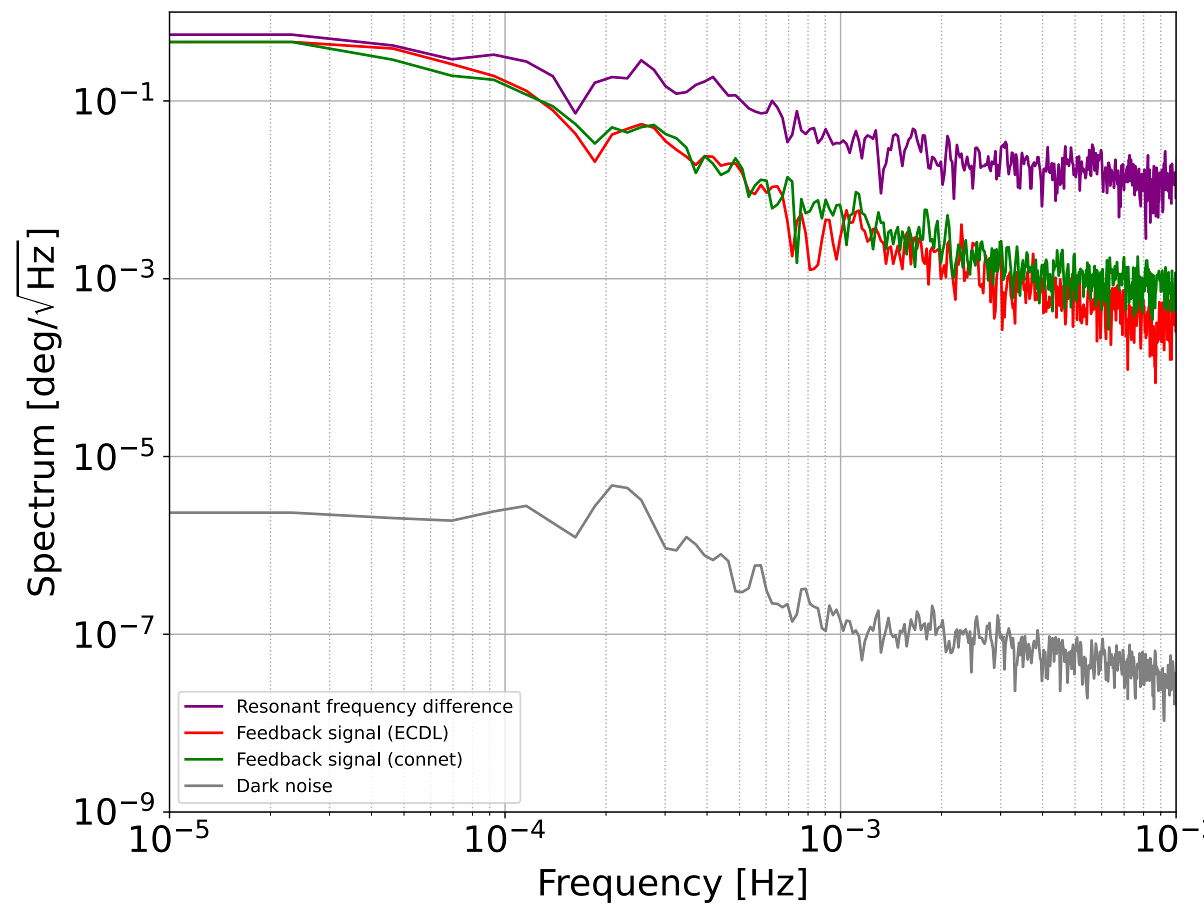
① Is the phase modulation frequency involved ?

② Is there any problems in control system ?

③ Do s- or p-pol. mix in the RFPD and make it difficult to lock long term ?

Noise reduction for folded cavity experiment





$$\delta f = \frac{1}{1+G}\delta f_0 - \frac{AFS}{1+G}\delta L - \frac{G}{1+G}n$$

Possibility of dominant noise

Intensity noise may be mixed in frequency noise

⟹ Specify the noise source

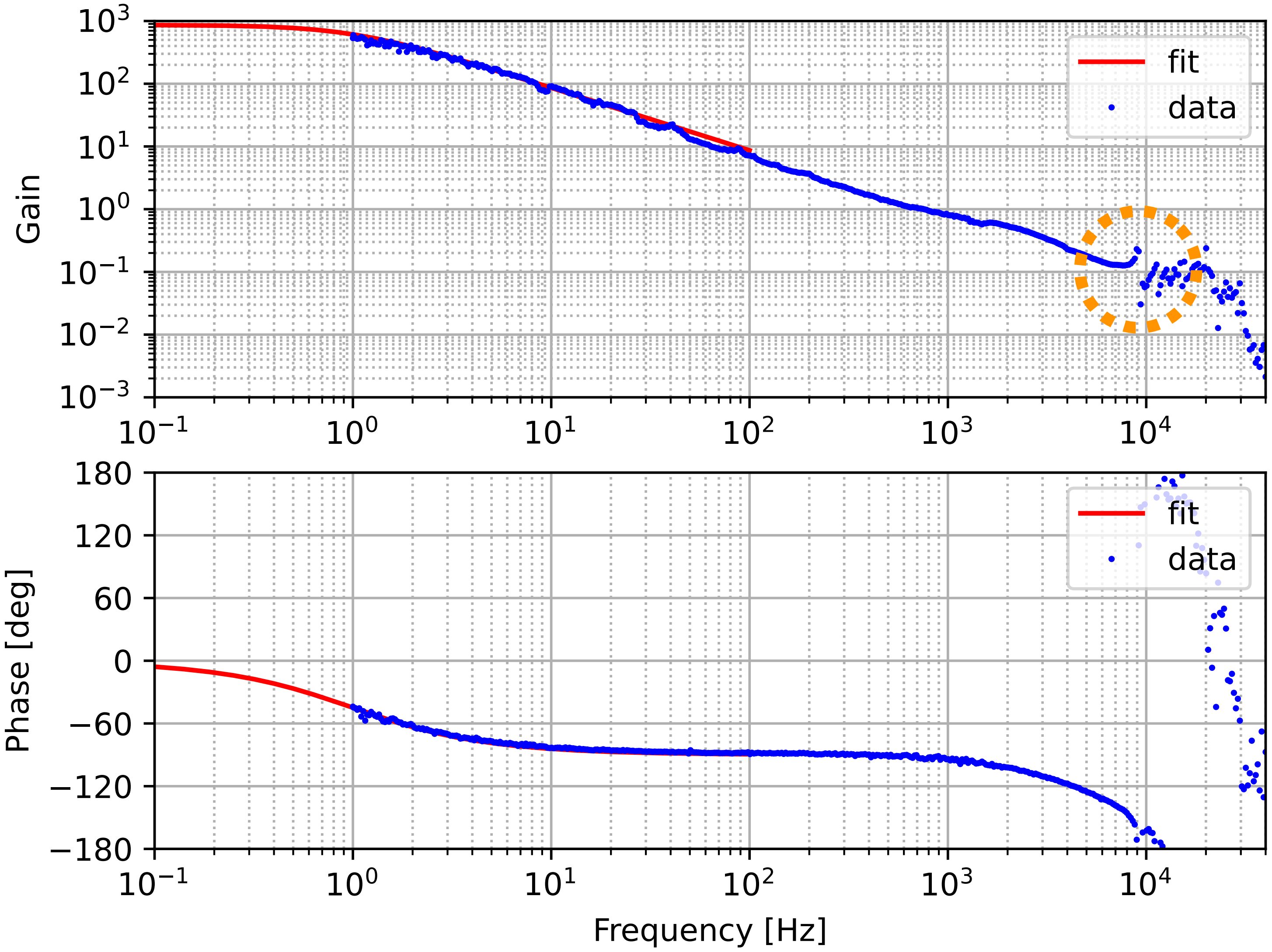
Noise reduction for folded cavity experiment

Suppress fluctuation by improving control gain

⟹ Need to do current control due to resonant structure at around 10 kHz

Obtain time drift of reflection phase difference that satisfies the requirement for simultaneous resonance after noise reduction

⟹ Can I write a paper ?



Improvement of shot noise limit for DANCE

The cause of limiting the output power from diode laser

- Catastrophic Optical Damage (COD) of face deteriorates the device
- Laser characteristics deteriorate due to increase in temperature of optics

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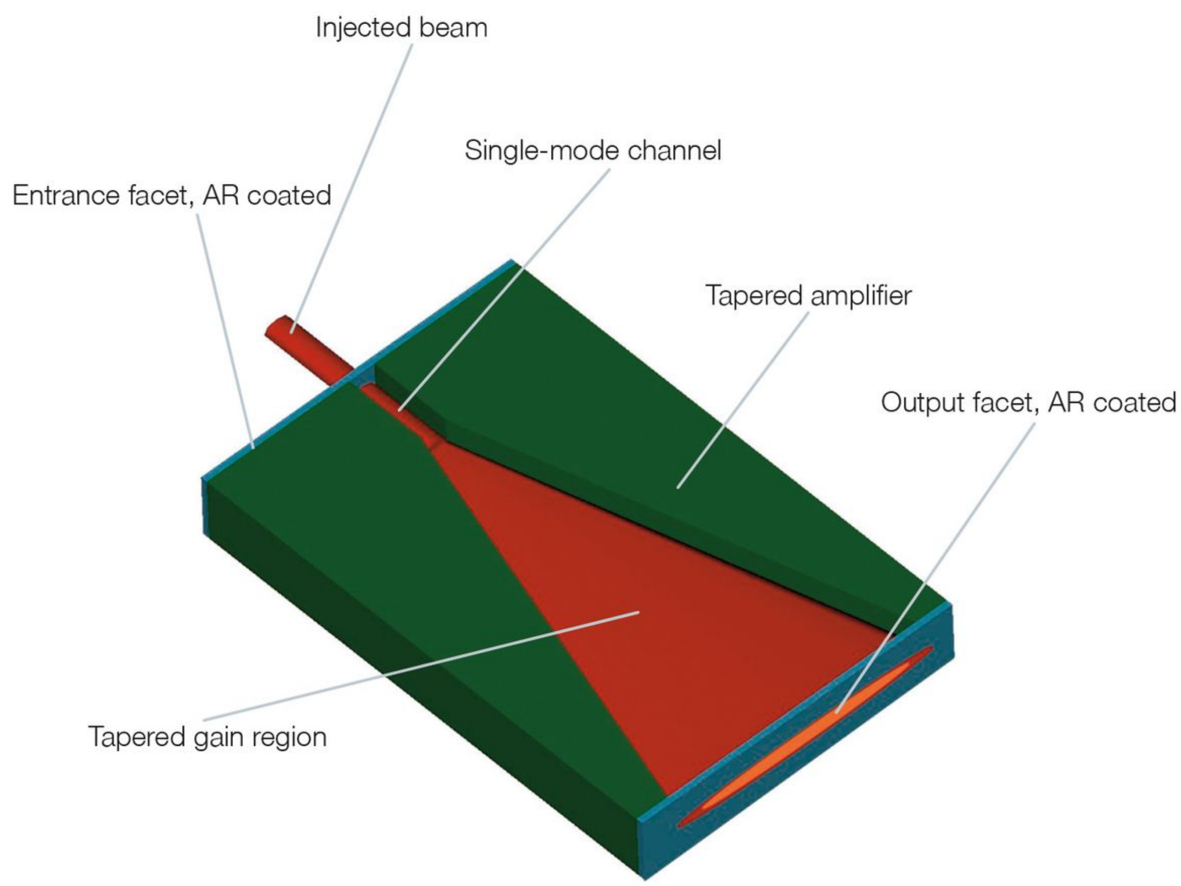
Is high power with a power amplifier achievable?



Concern

- Thickness of mirror coating may change

⇒ Reflection phase difference changes

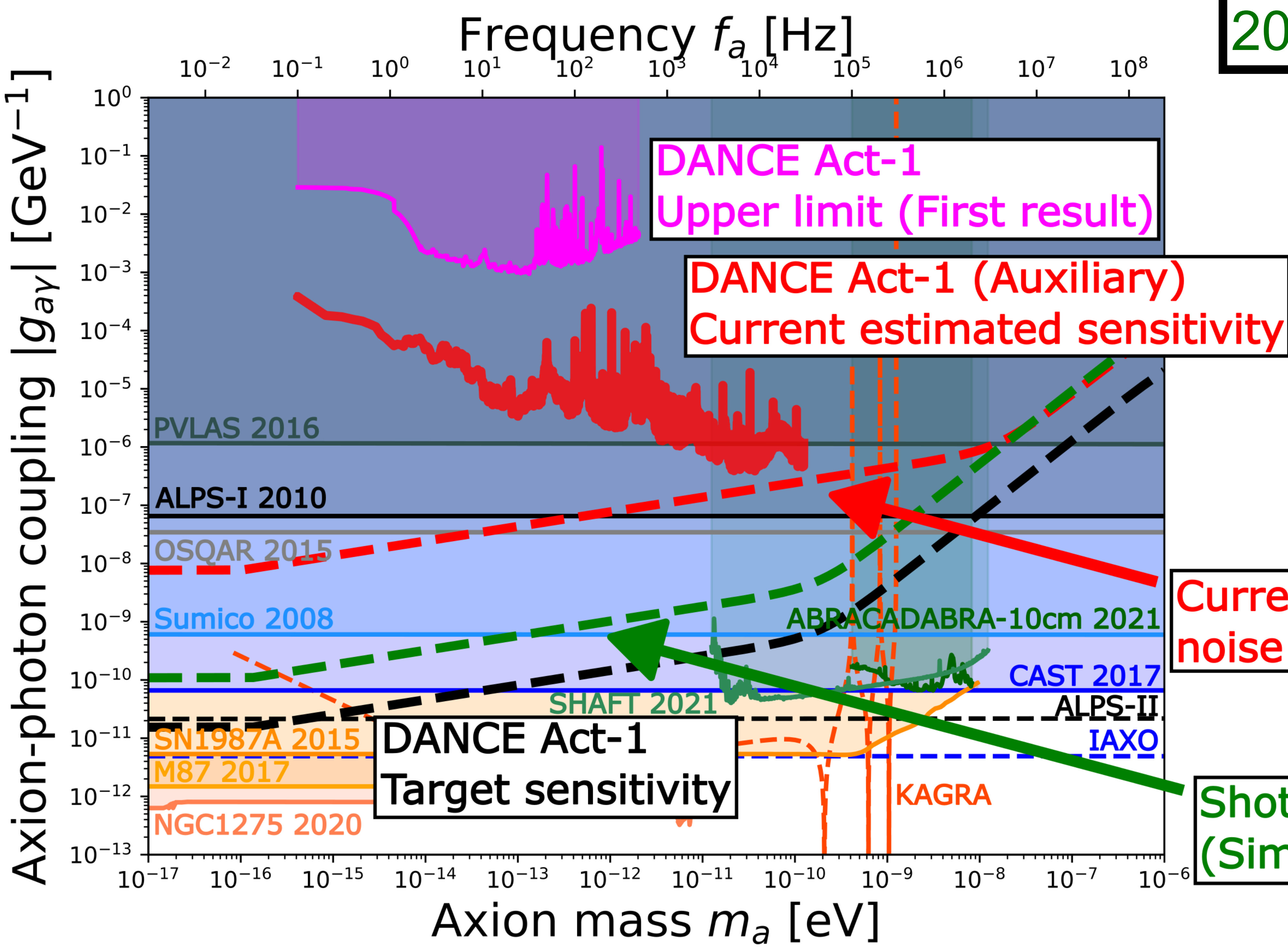
- Mirror may be damaged

https://www.toptica.com/ja/technology/technical-tutorials/tapered-amplifiers

Improvement of shot noise limit for DANCE

- Improved by 2 orders of magnitude achieving simultaneous resonance
- Improved by 1 orders of magnitude realizing high power laser

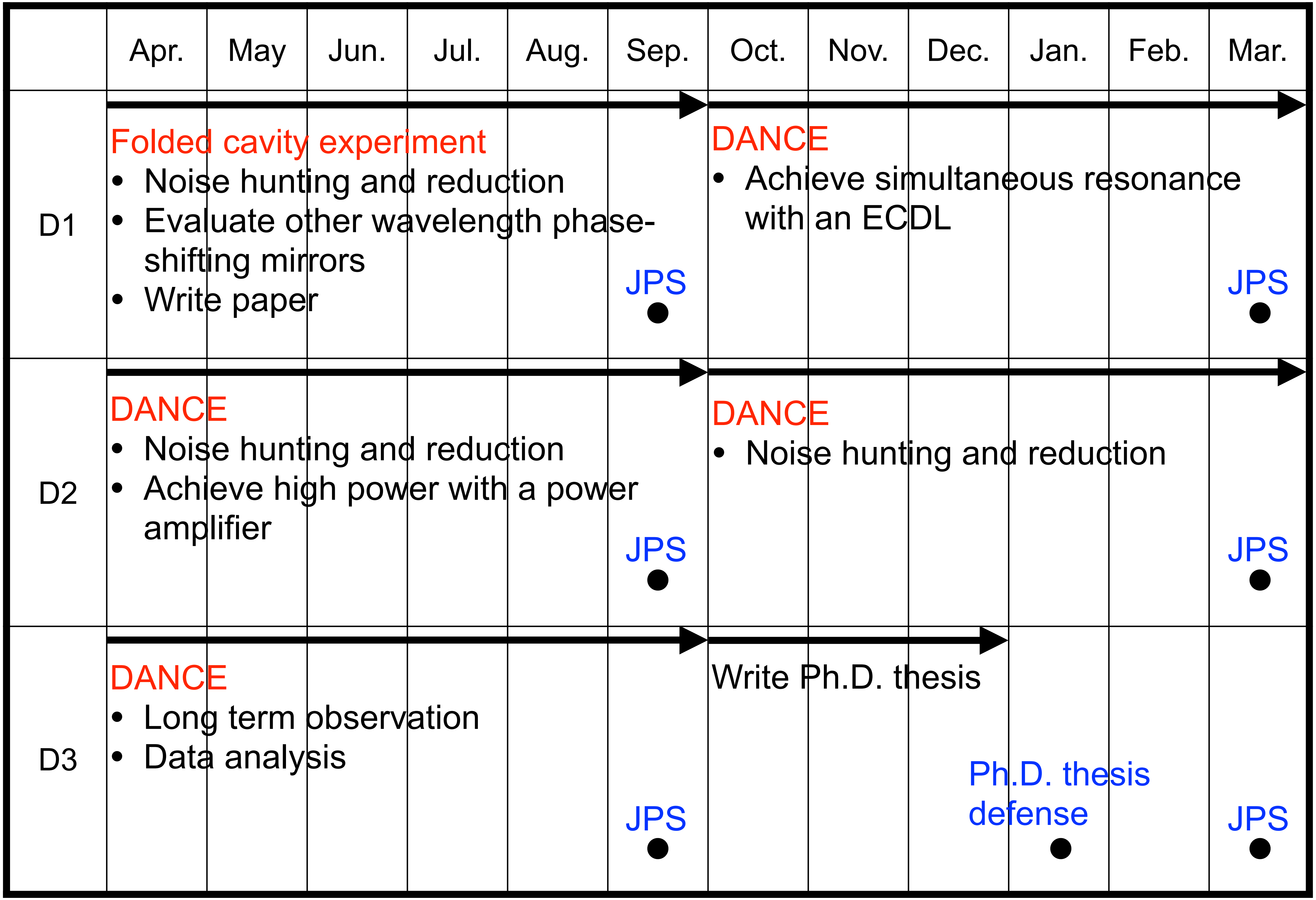
20mW ⇨ 1W



Current shot noise limit

Shot noise limit (Simultaneous resonance)

Schedule toward Ph.D.



Contents

Summary

DANCE (Dark matter Axion search with riNg Cavity Experiment)

- Dark matter axion search with a bow-tie optical ring cavity by detecting a rotation angle of linearly polarized light
- Establishment of simultaneous resonance with a folded cavity is in progress
- DANCE with an ECDL is also in progress
- Achieve the world's most sensitive dark matter axion search