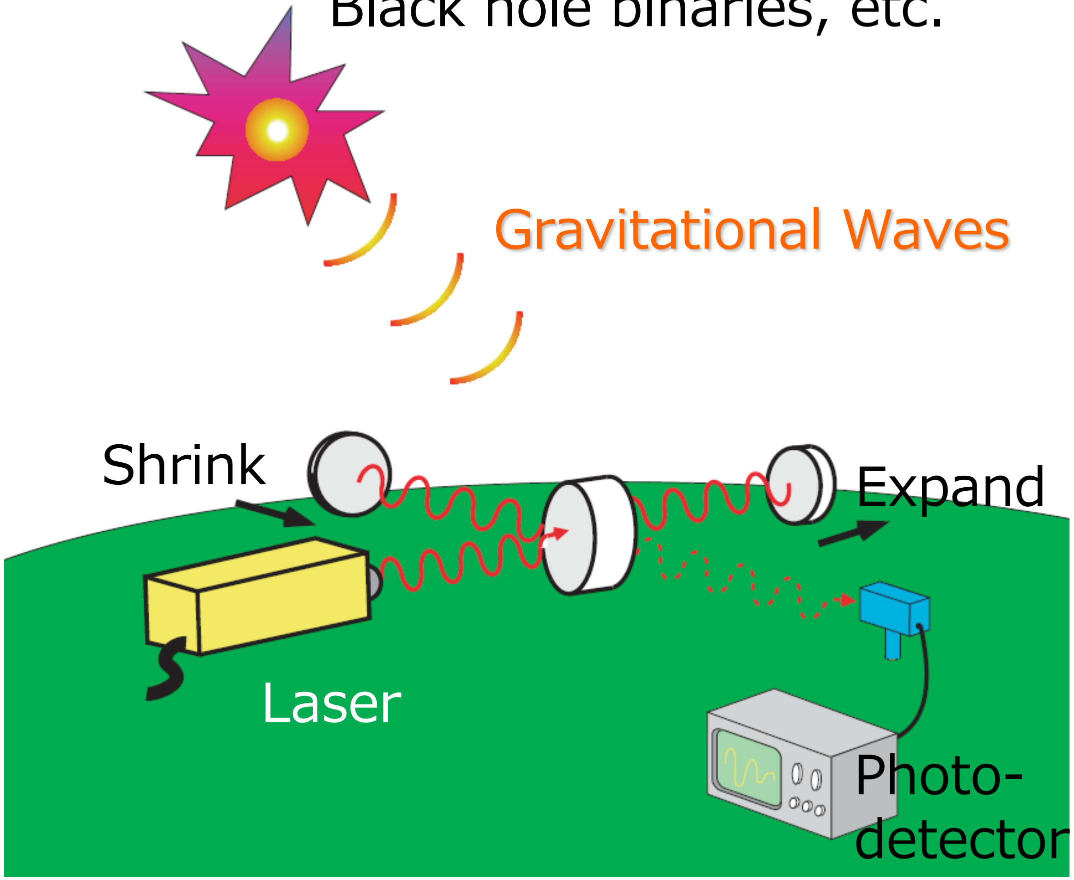
# Current status of the intracavity OPO experiments at Tokyo Tech

AIC telecon
Jun 2020

Tokyo Inst. of Tech.
K.Somiya, S.Otabe, and K.Harada

K.Somiya

# Gravitational wave telescopes



Far Galaxy

Supernova explosion,
Black hole binaries, etc.

Gravitational Waves

Shrink

Expand

Laser

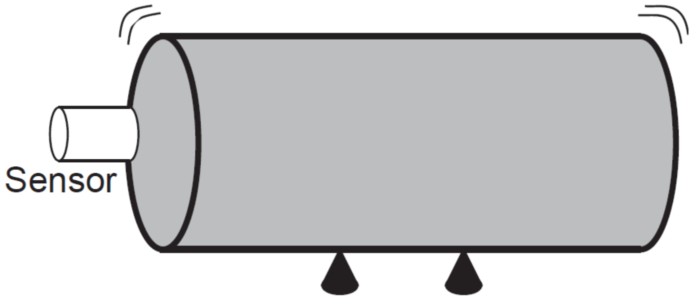
Photo-detector

Earth

- aLIGO in US [4km]
- AdVirgo in Italy [3km]
- GEO-HF in Germany [600m]
- KAGRA in Japan [3km]

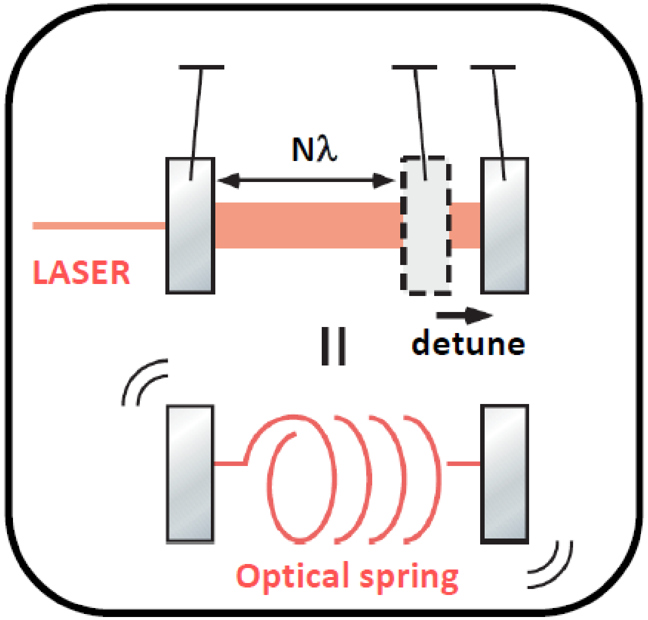
**The sensitivity at high freq is limited by photon shot noise.**

# Mechanical and optical bars



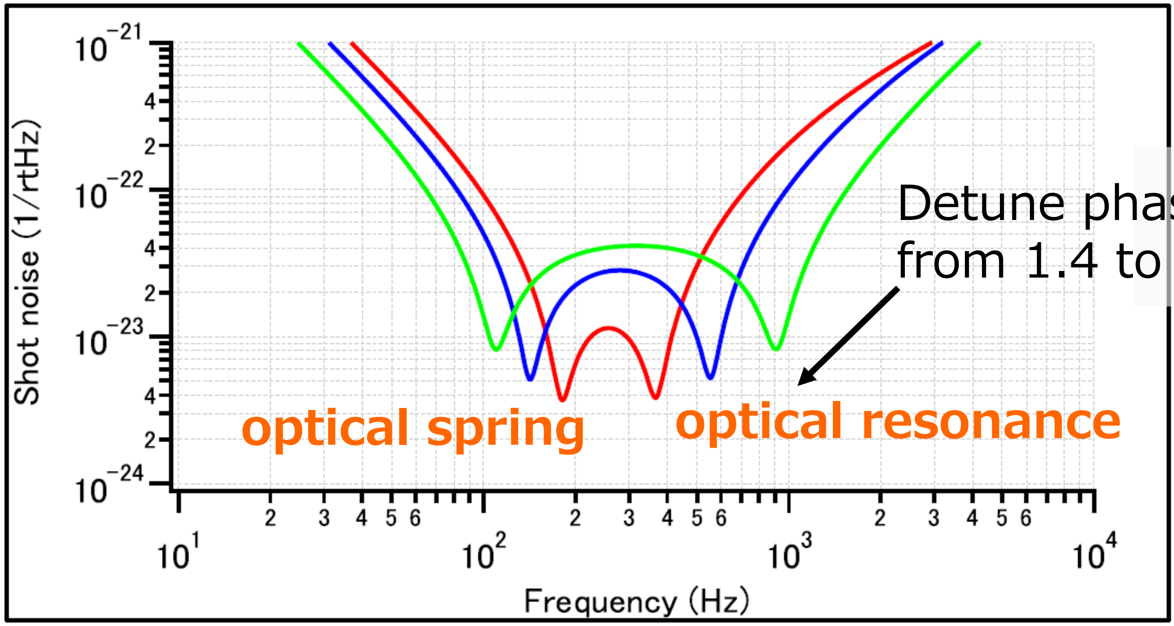
**Resonant frequency**

$$f = \frac{1}{2L}\sqrt{\frac{E}{\rho}}$$



- Susceptibility to GW increases at its resonance
- Sensitivity of a mech bar cannot be as good as the optical IFOs for its limited length

# Optical spring frequency



optical spring

optical resonance

Detune phase is changed from 1.4 to 1.2 deg.

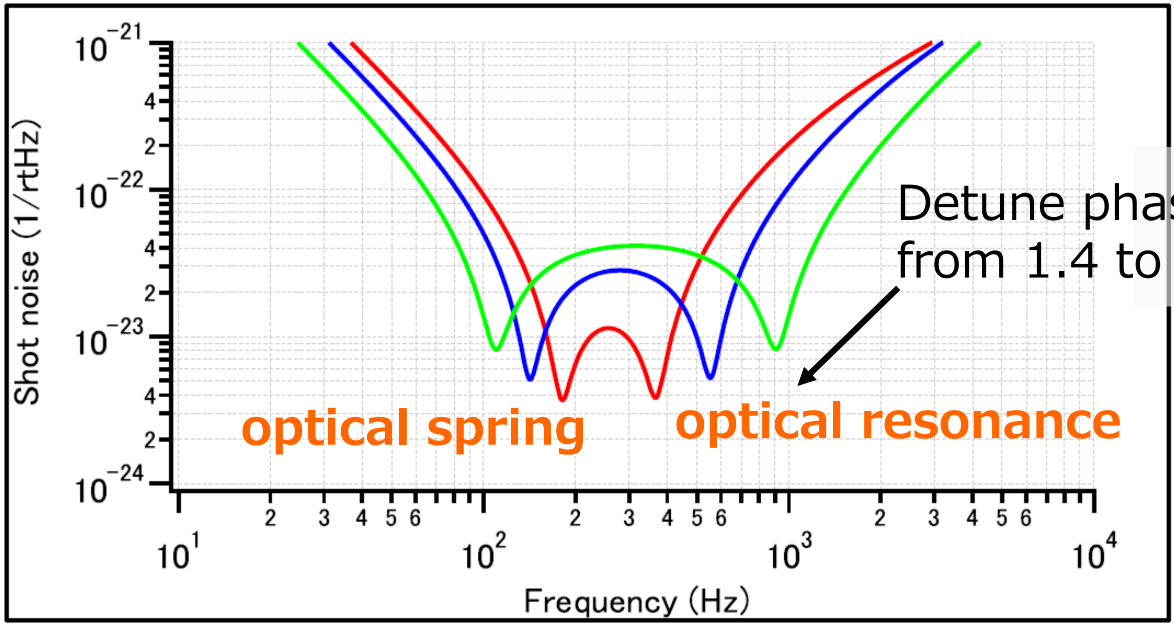
**Optical spring** $$\Omega \propto \sqrt{\frac{\sin 2\phi}{\left(r+\frac{1}{r}\right)-2\cos 2\phi}}$$

decrease with the detune phase $\phi$

**Optical resonance** $$\Omega \propto \frac{\sin 2\phi}{\left(r+\frac{1}{r}\right)+2\cos 2\phi}$$

increase with the detune phase $\phi$

# Optical spring frequency



optical spring

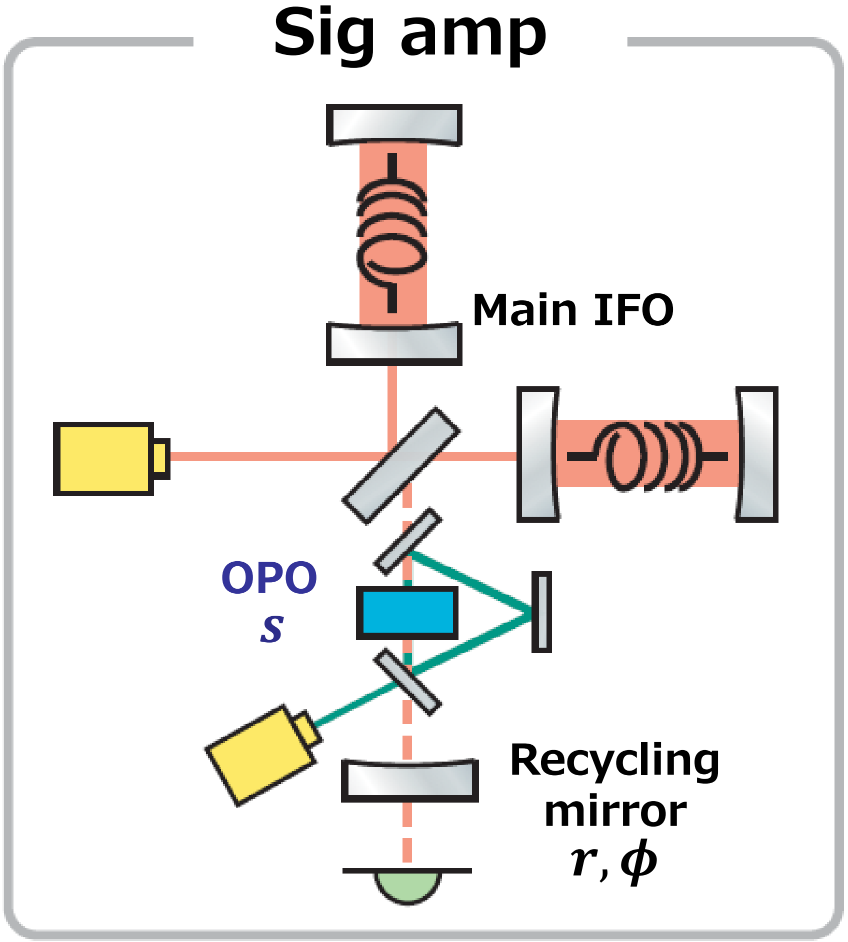
optical resonance

Detune phase is changed from 1.4 to 1.2 deg.

**Spring freq is lower than optical resonance.**
**Highest frequency is given with** $\Omega_{\mathrm{spr}} = \Omega_{\mathrm{reso}} \rightarrow \quad \Omega \cong \sqrt[3]{\frac{8 I_c \omega_0}{mLc}}$

**Optical spring stiffness is given by the circulating power, arm length, and the mirror mass.**

# Parametric signal amplification



**Optical spring w/o OPO**

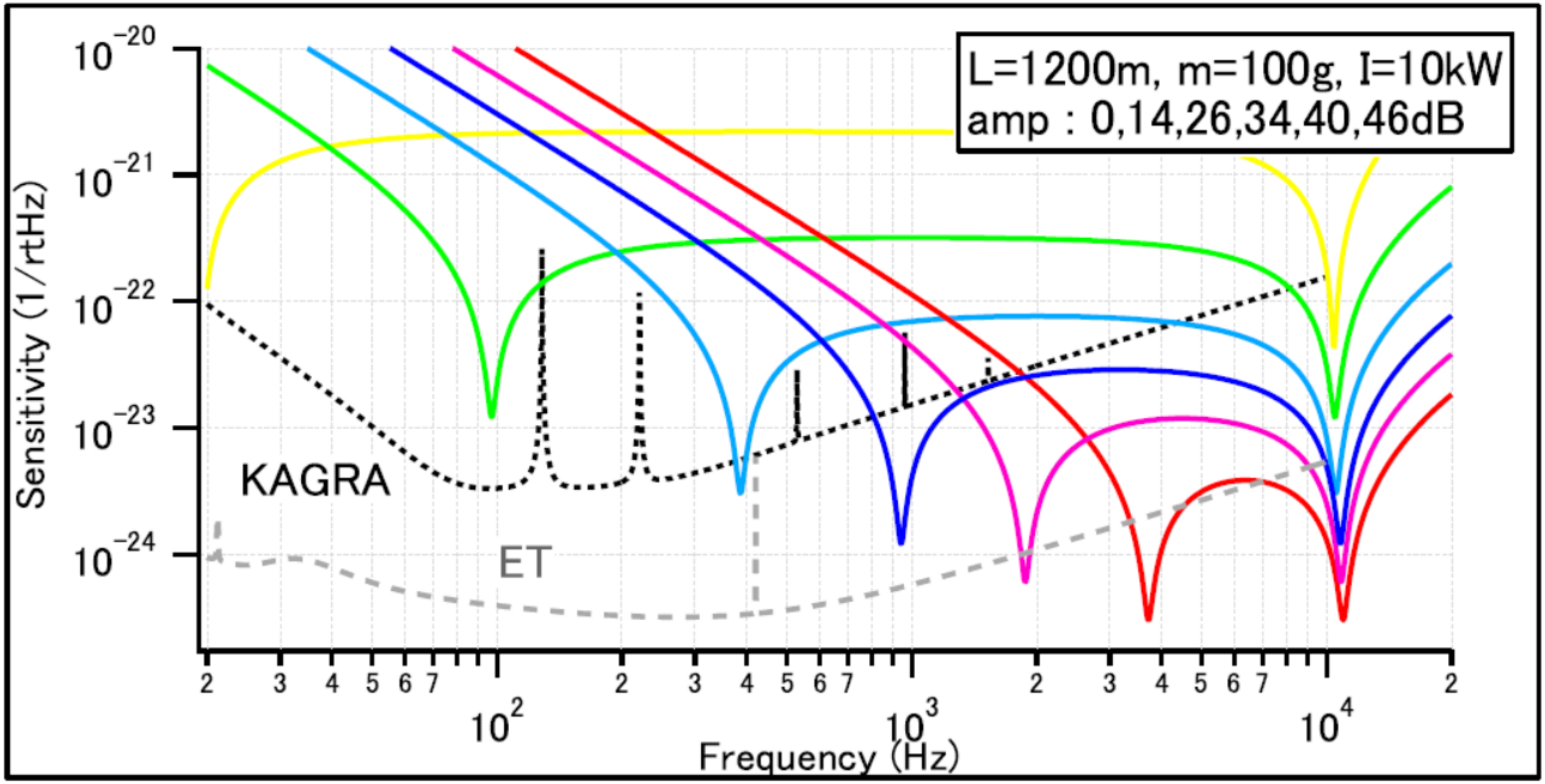
$$\Omega \propto \sqrt{\frac{\sin 2\phi}{\left(r + \frac{1}{r}\right) - 2\cos 2\phi}}$$

**Optical spring with OPO**

$$\Omega \propto \sqrt{\frac{s \times \sin 2\phi}{\left(r + \frac{1}{r}\right) - \left(s + \frac{1}{s}\right)\cos 2\phi}}$$

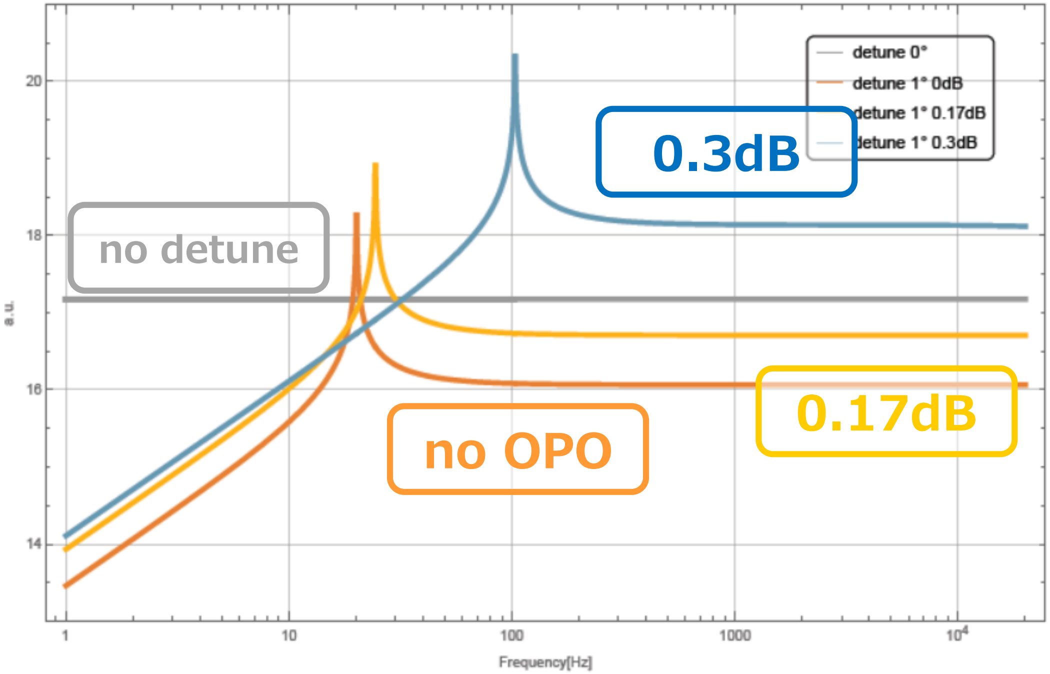
**Optical spring frequency can be enhanced by tuning the OPO gain *s*.**

# Sensitivity improvement at HF



- **Optical losses are not included; will degrade the sensitivity by one order of magnitude**
- **Attractive configuration for a 2.5-3G detector**

# Proof-of-principle experiments



**[Shot noise improvement test]**
- **detune phase ~ 45 deg**
- **squeezing factor ~ 30dB+**
- **low classical noise**

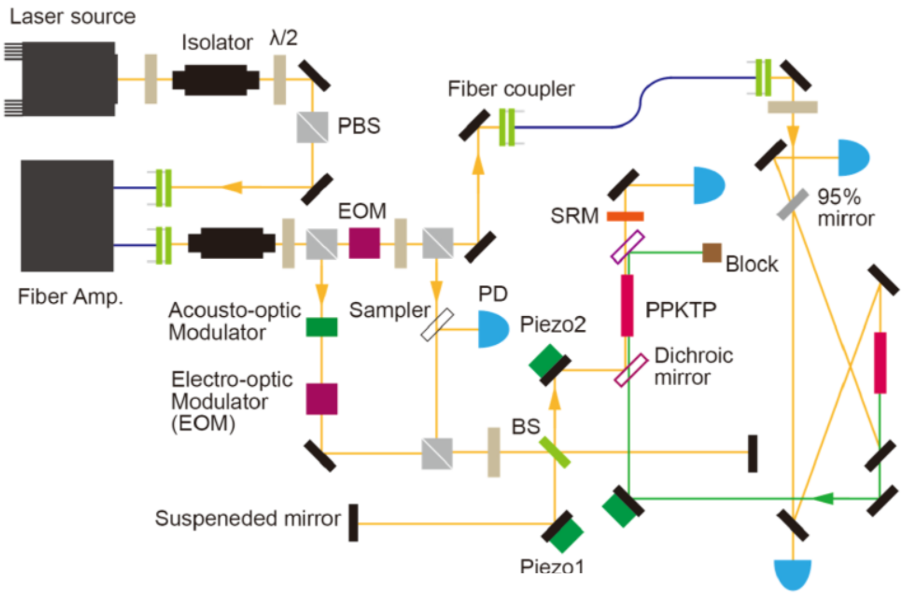
**[Transfer function measurement]**
- **detune phase ~ 1 deg**
- **squeezing factor ~ 0.3dB (with our current SRMI setup)**

**We set our first goal to observe the increase of optical spring frequency with an intracavity OPO.**

**A single-pass OPO is ok.**

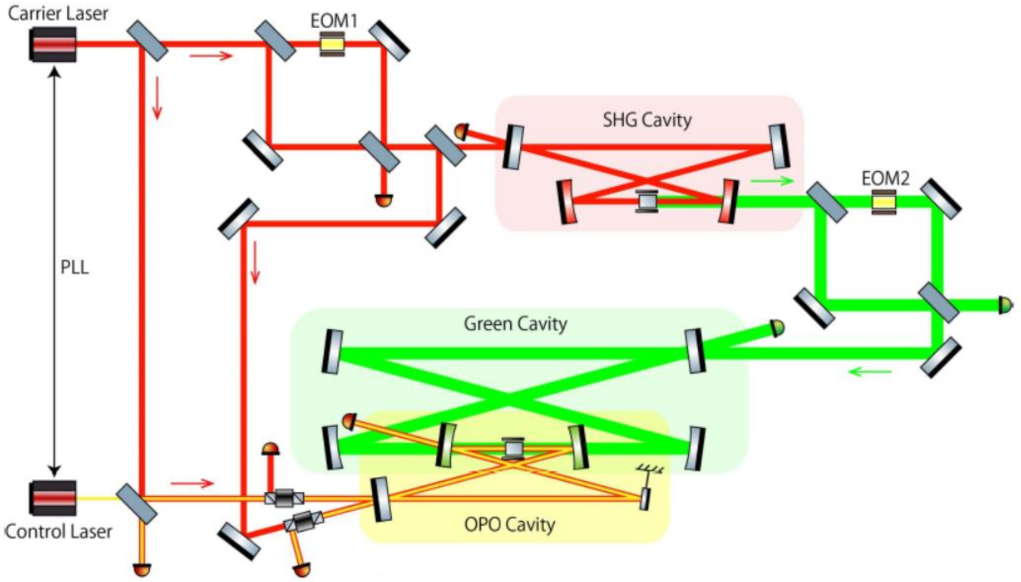
# Proof-of-principle experiments

## (1) Detuned Signal Recycling



- OPO in SR cavity
- High input power (<10W)
- Successful operation of SRMI
- 0.1dB Single-pass OPA
- 0.2dB lossy SRC OPO

## (2) Detuned Fabry-Perot cavity

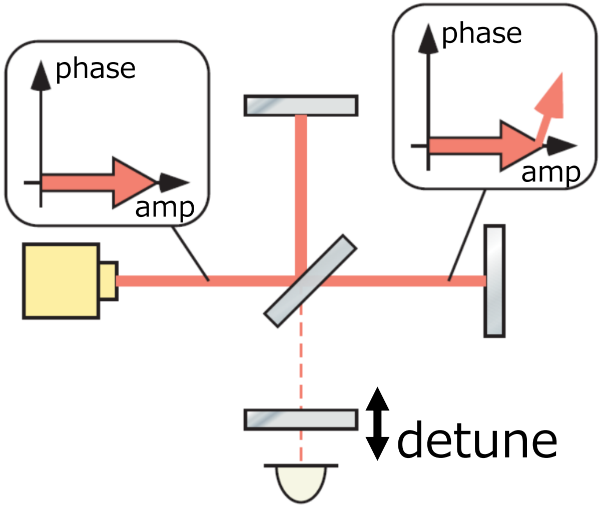


- OPO amplifies signal and deamplifies carrier, or vice versa
- Optical spring has been observed.

I will mainly talk about this experiment.

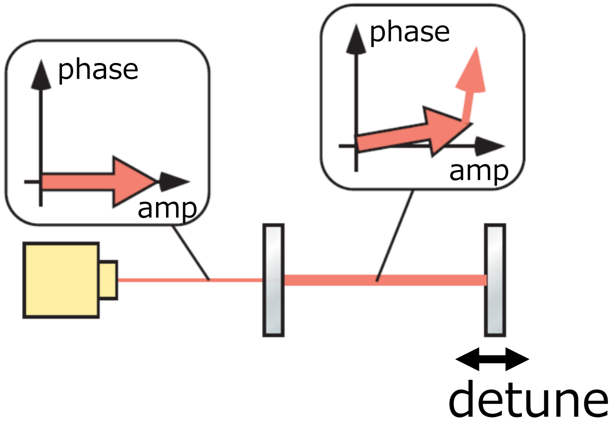
# Comparison of the configurations

## (1) Detuned Signal Recycling



- Carrier in amp. quad.
- Signal detuned from phase quad.

## (2) Detuned Fabry-Perot cavity

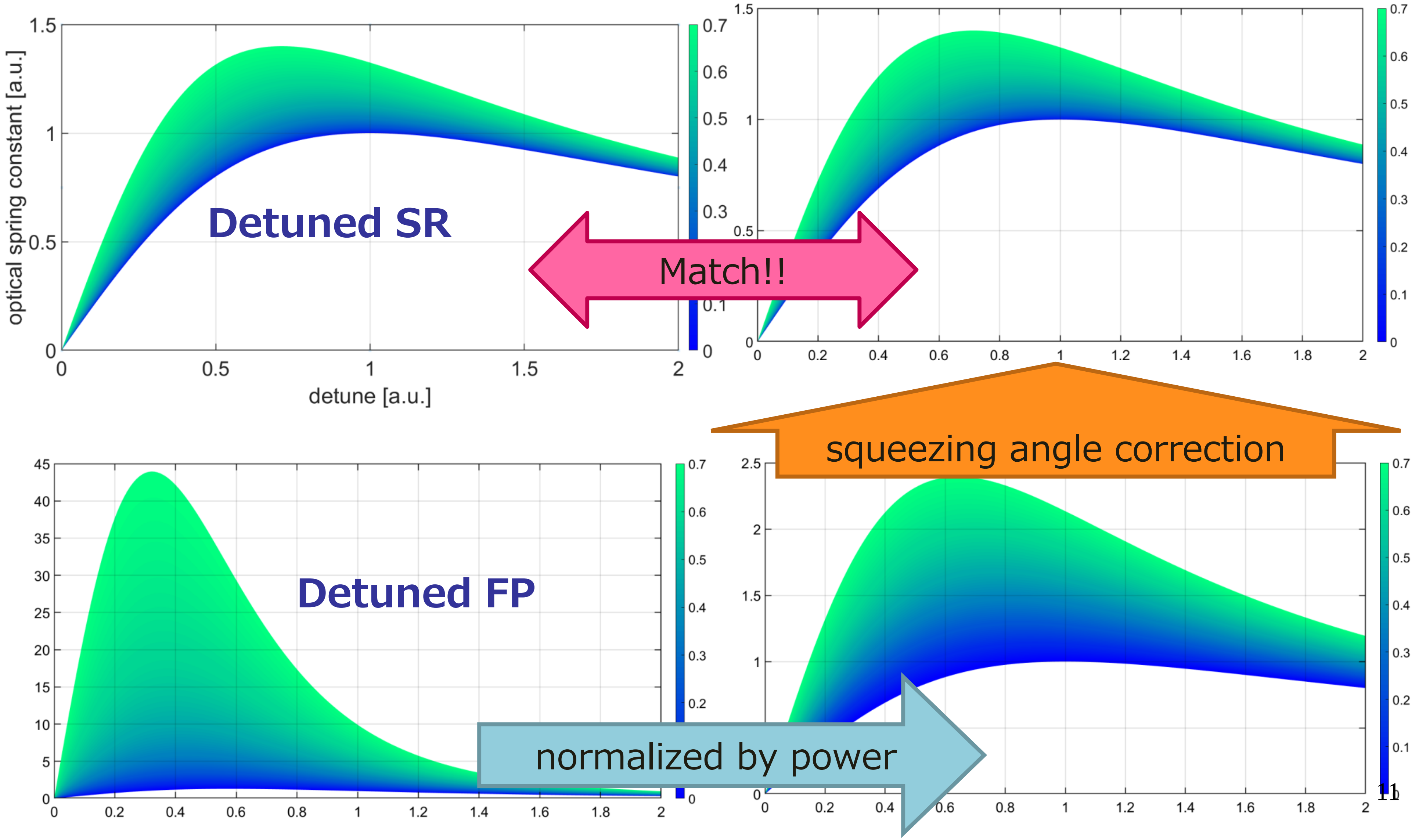


- Carrier detuned from amp. quad.
- Signal also detuned from phase

Optical spring effect is equivalent between the two configurations even with an intracavity OPO.

# Comparison of the configurations

[Otabe, 2019]



**Detuned SR**

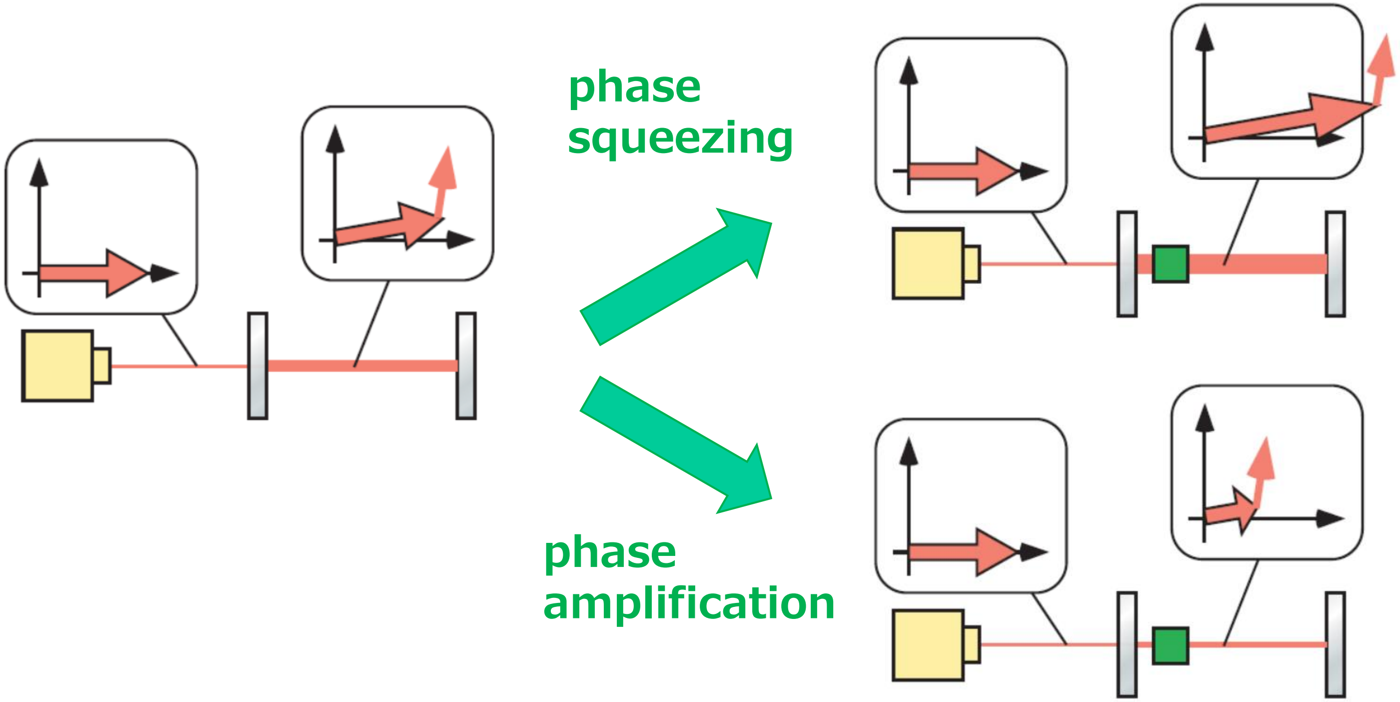
Match!!

squeezing angle correction

**Detuned FP**

normalized by power

# Two regimes to use the intra-OPO



phase
squeezing

phase
amplification

**Optical spring freq.**

$$\Omega \propto \sqrt{\frac{s \times \sin 2\phi}{\left(r+\frac{1}{r}\right)-\left(s+\frac{1}{s}\right)\cos 2\phi}}$$

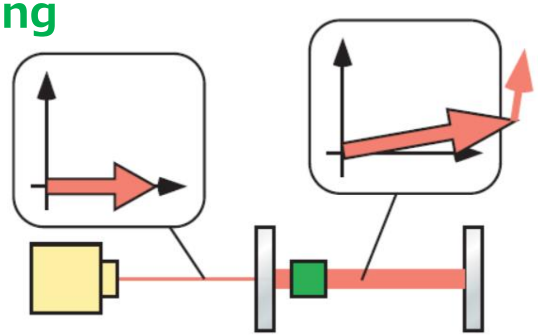
increases/decreases with
phase amplification/squeezing

approaches to zero with
phase amplification/squeezing

**Either regime works to increase the spring frequency.**

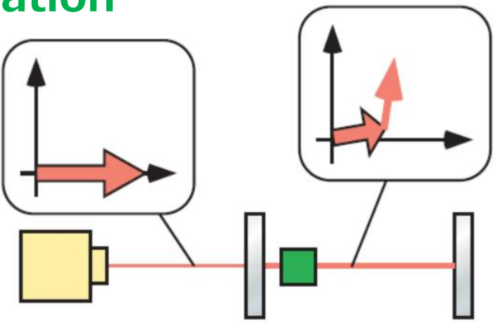
# Challenges in each regime

**Phase squeezing**



- Signal amplification is lower after normalizing it by the carrier power

**Phase amplification**



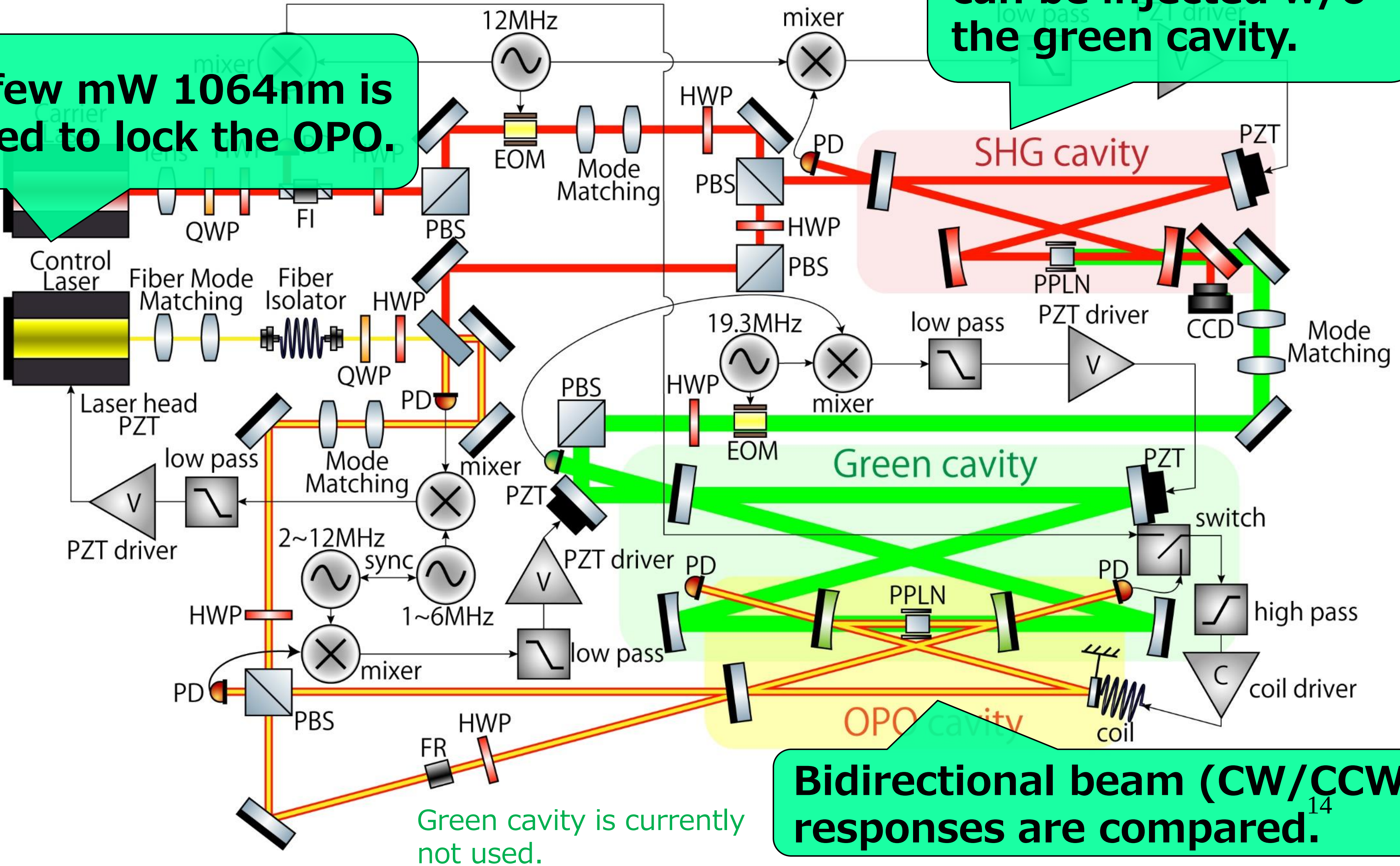
- Signal decreases until the critical coupling condition is almost met
- Control signals decrease according to the carrier deamplification

We have decided to try the phase squeezing regime.

# Experimental setup

**A few mW 1064nm is used to lock the OPO.**

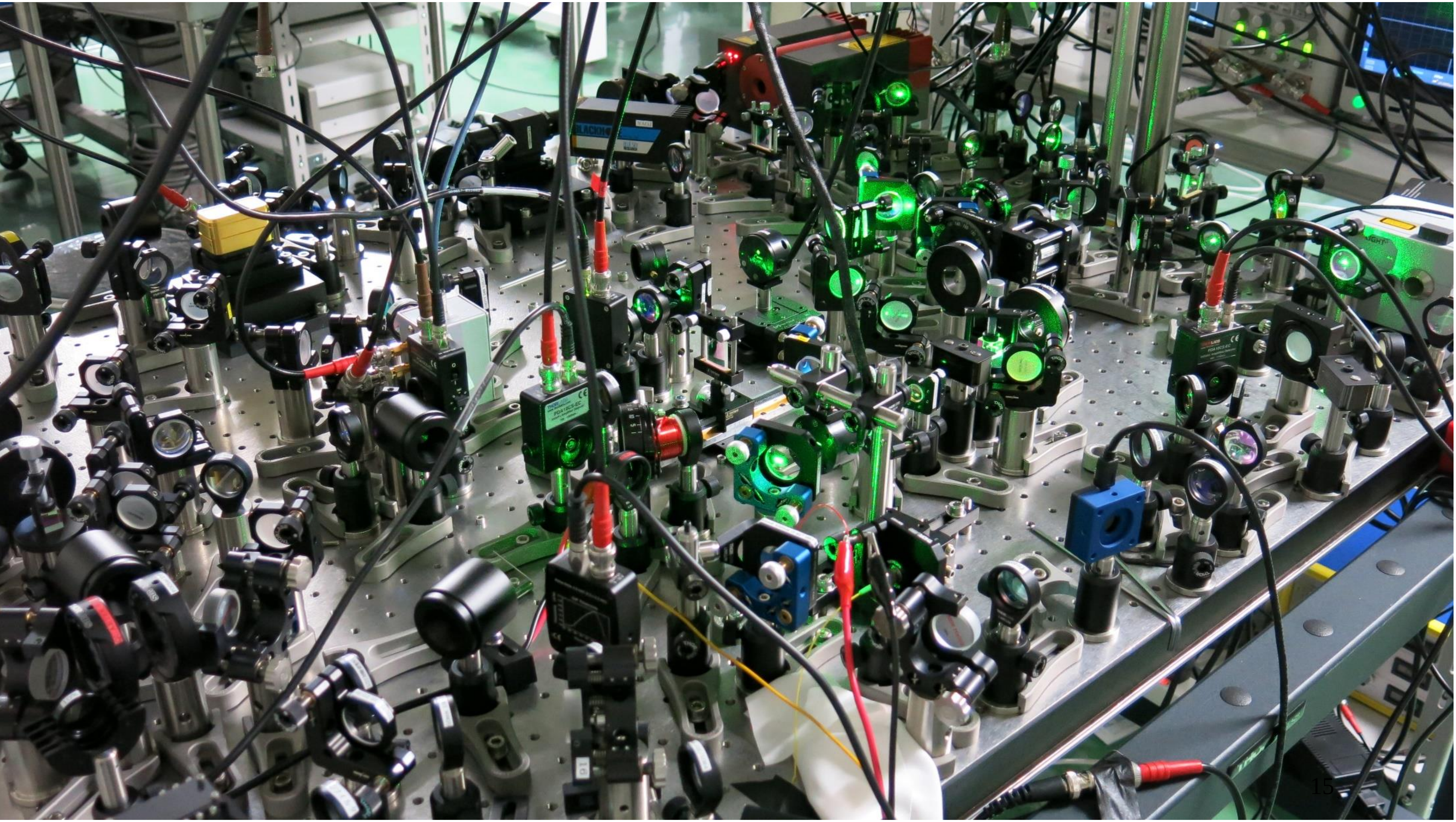
**Max ~500mW green can be injected w/o the green cavity.**



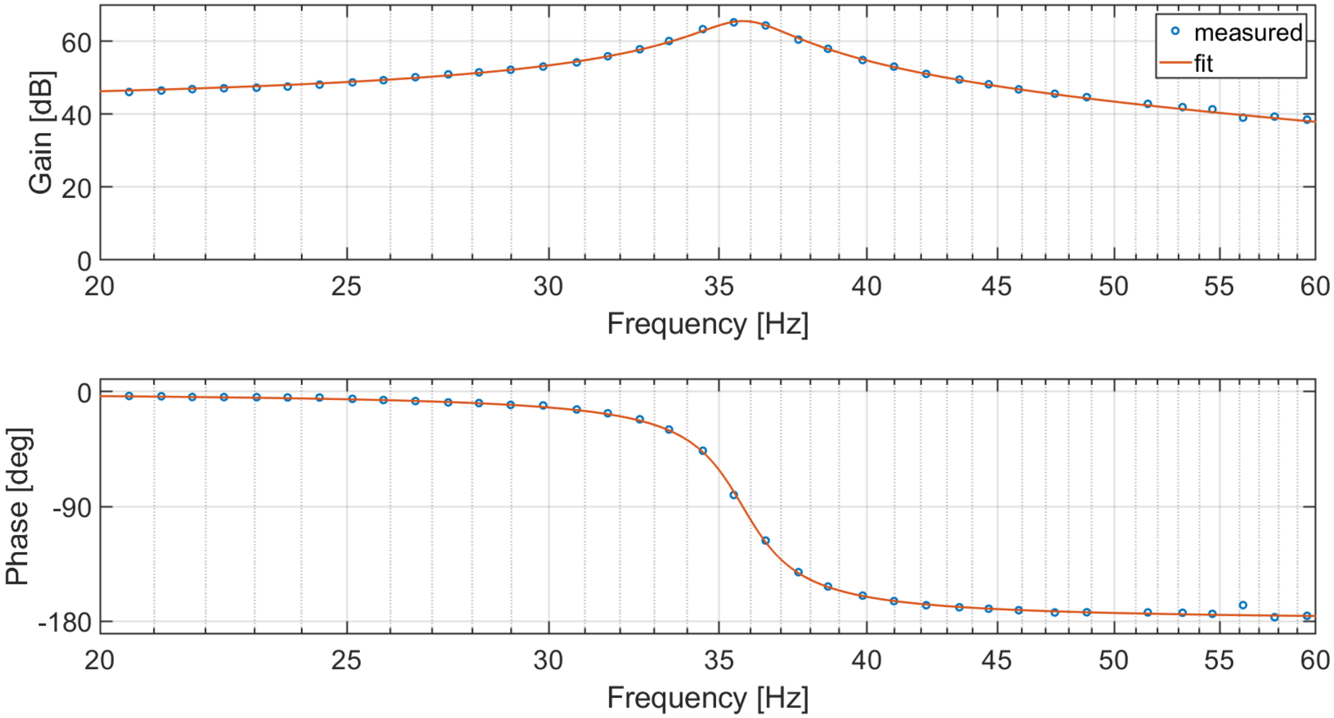
Green cavity is currently not used.

**Bidirectional beam (CW/CCW) responses are compared.**

# Experimental setup

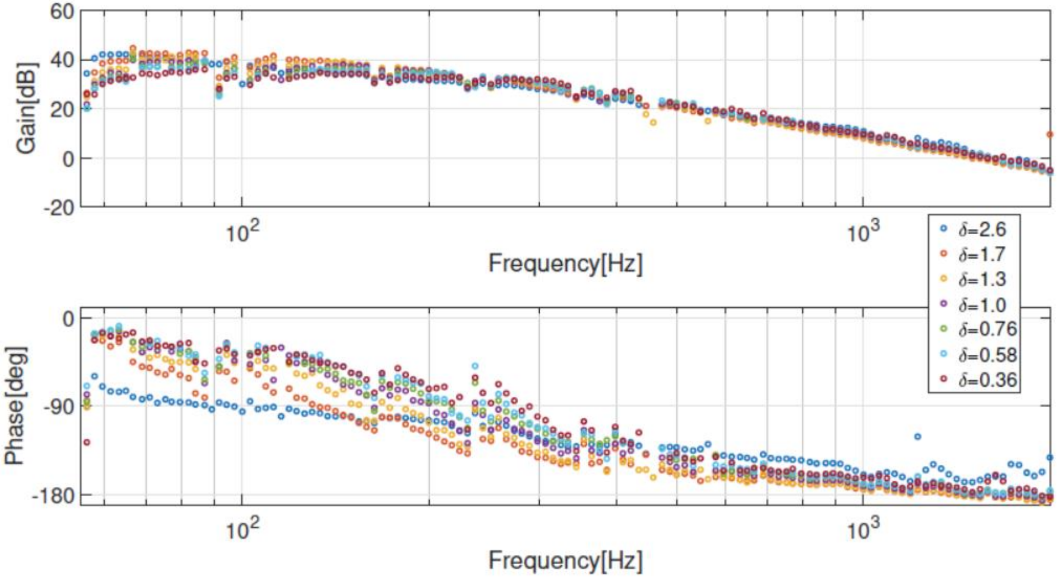


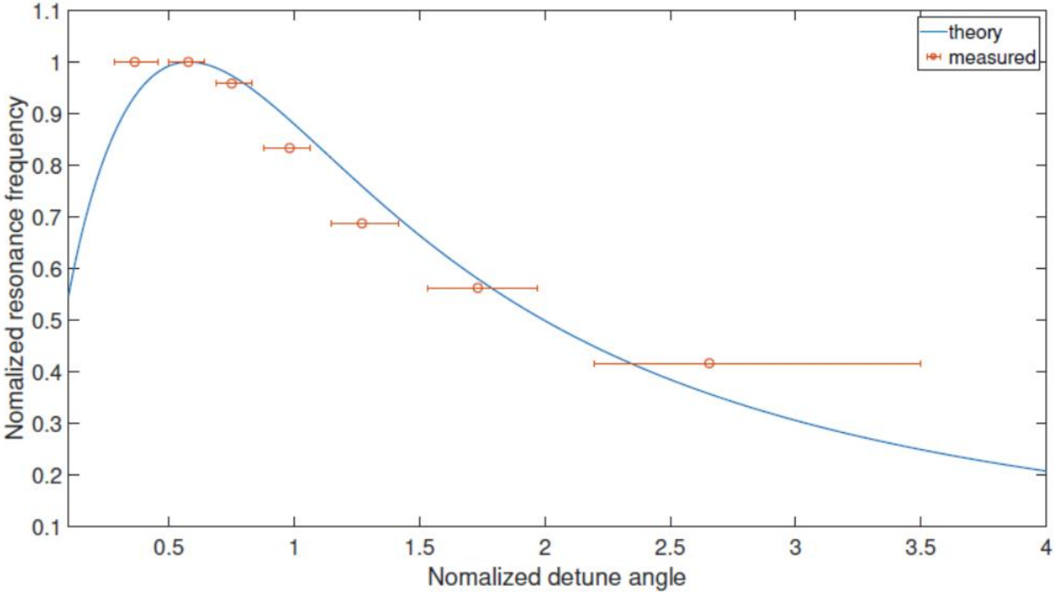
# Oscillator



A ~210mg mirror is mounted in a double-side spiral suspension system (PET and BeCu). The mechanical resonances are 10Hz and 35.7Hz, respectively.

# Optical spring



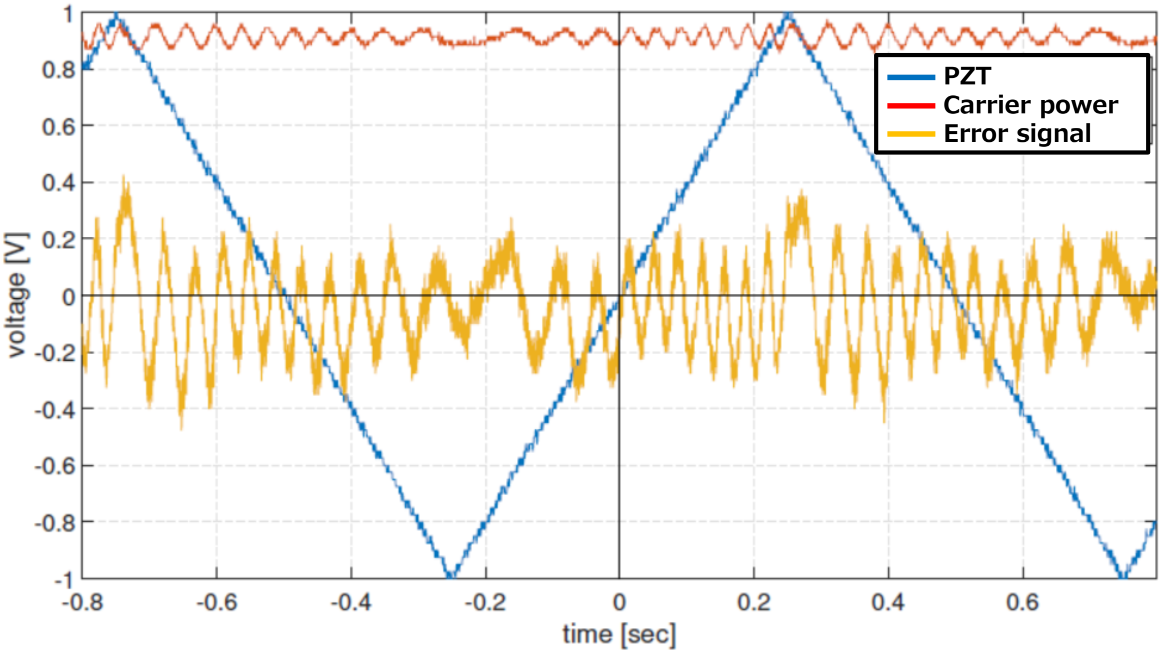


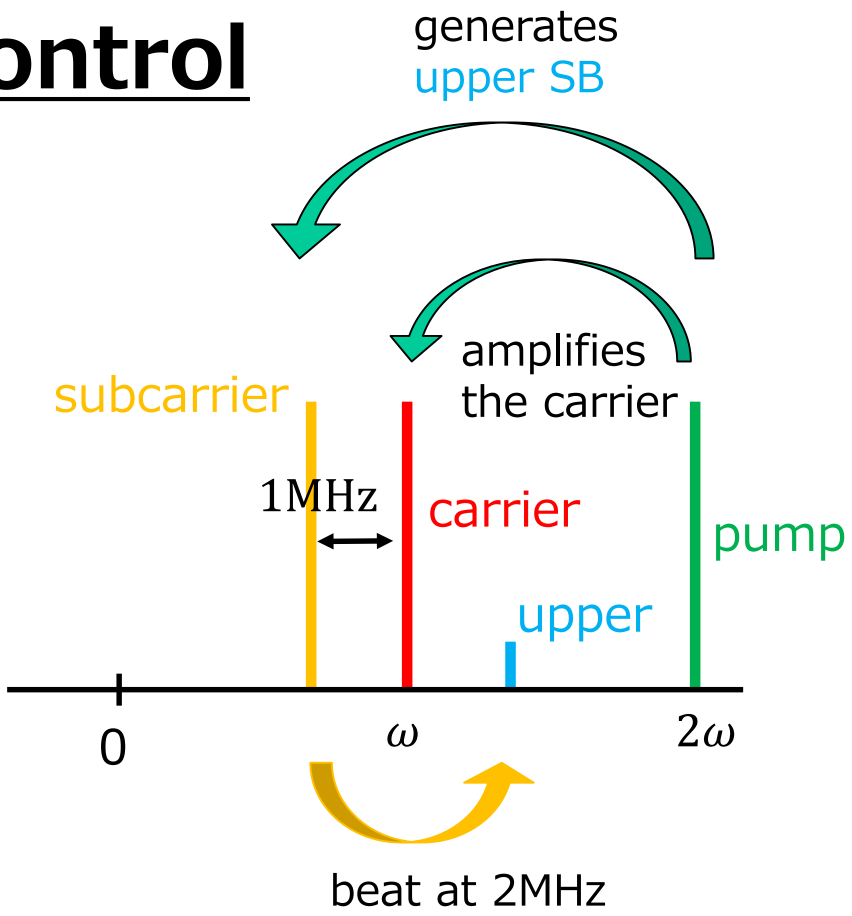
We measured the transfer function of the FP cavity without the OPO.

We saw that the resonant frequency decreases with the increasing detune phase owing to the optical spring.

$m = 210\text{mg},$
$F = 1000,$
$P_{in} = 140\text{mW}$
$\rightarrow f_{opt} = 250\text{Hz}$

# OPO phase control




generates
upper SB

amplifies
the carrier

subcarrier

1MHz

carrier

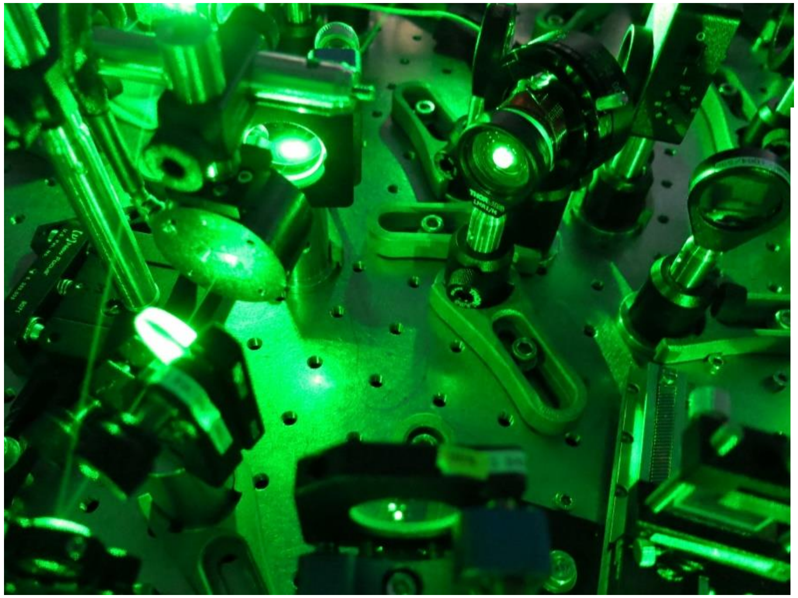
pump

upper

beat at 2MHz

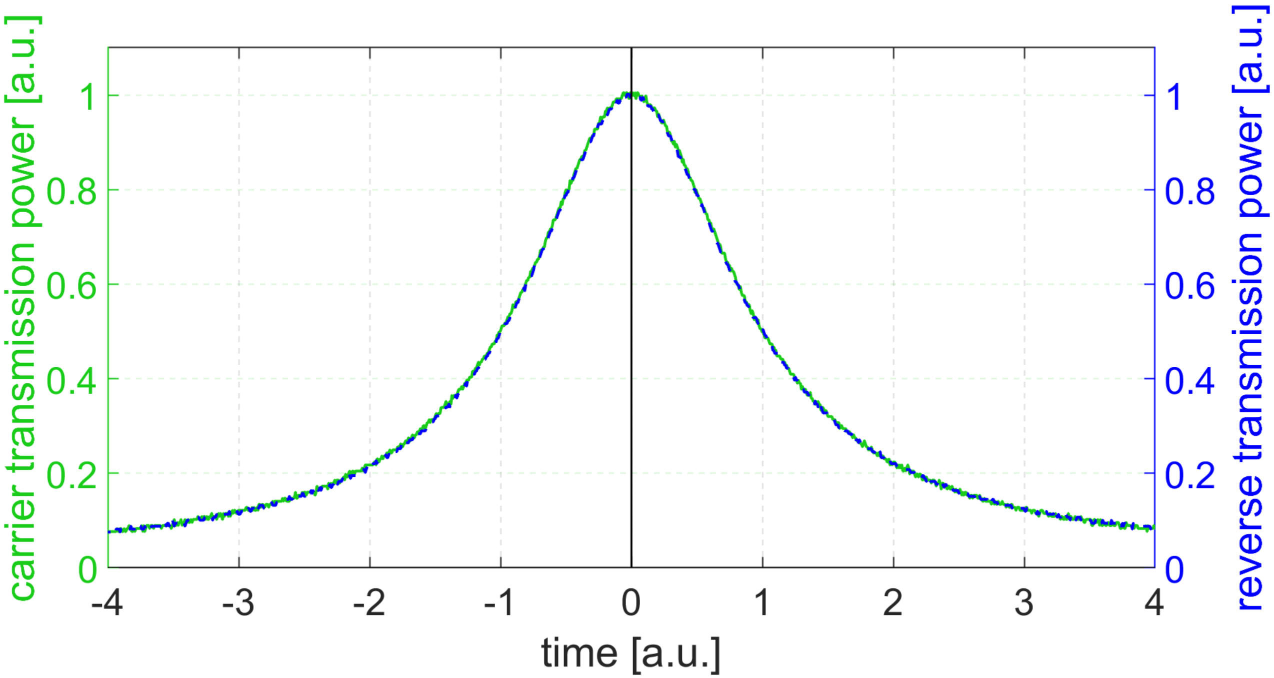
OPO phase is controlled to its operation point using the beat signal of the subcarrier and a field generated in OPO.

# Signal amplification experiment



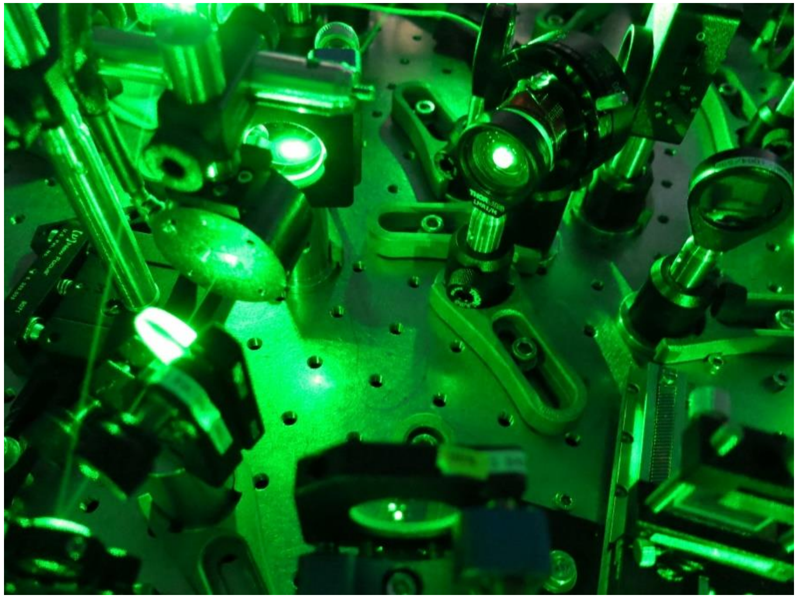
OPO cavity

## (1) Without OPO.



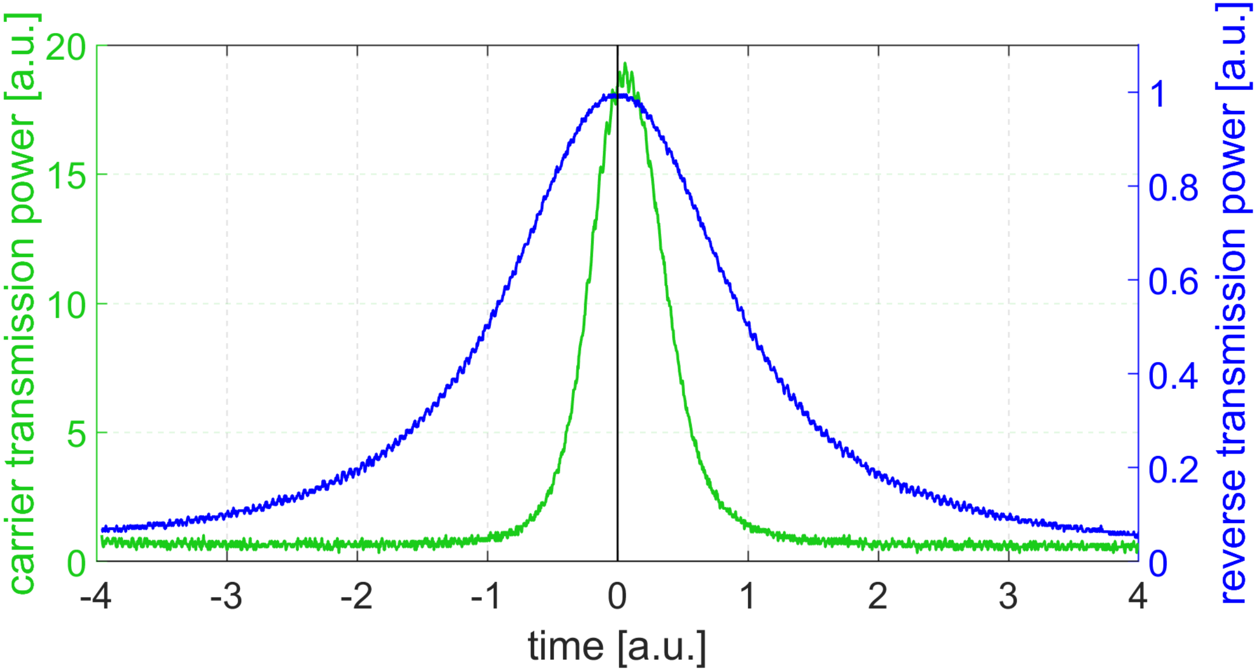
The transmission power and the Lorentzian function were measured simultaneously for the forward and reverse beams in the OPO cavity. Here the finesse is ~300.

# Signal amplification experiment



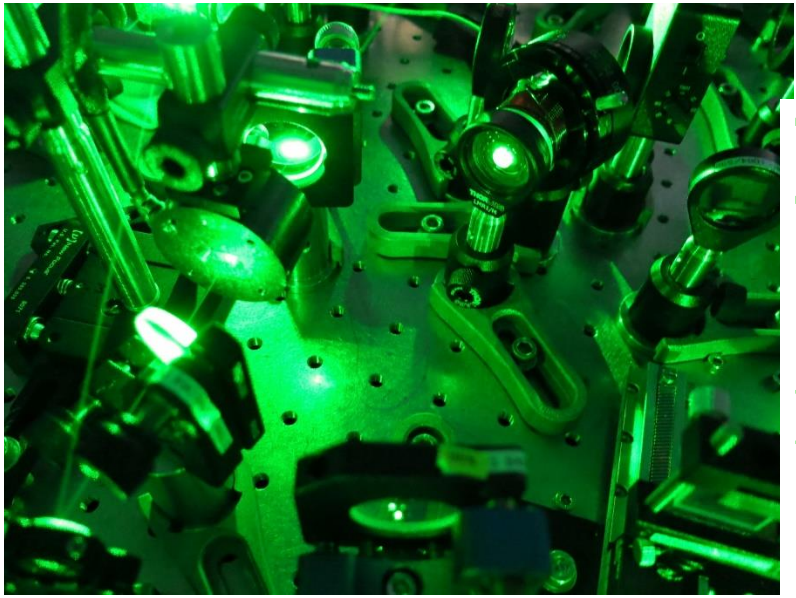
OPO cavity

## (2) With OPO; 0.6mW input



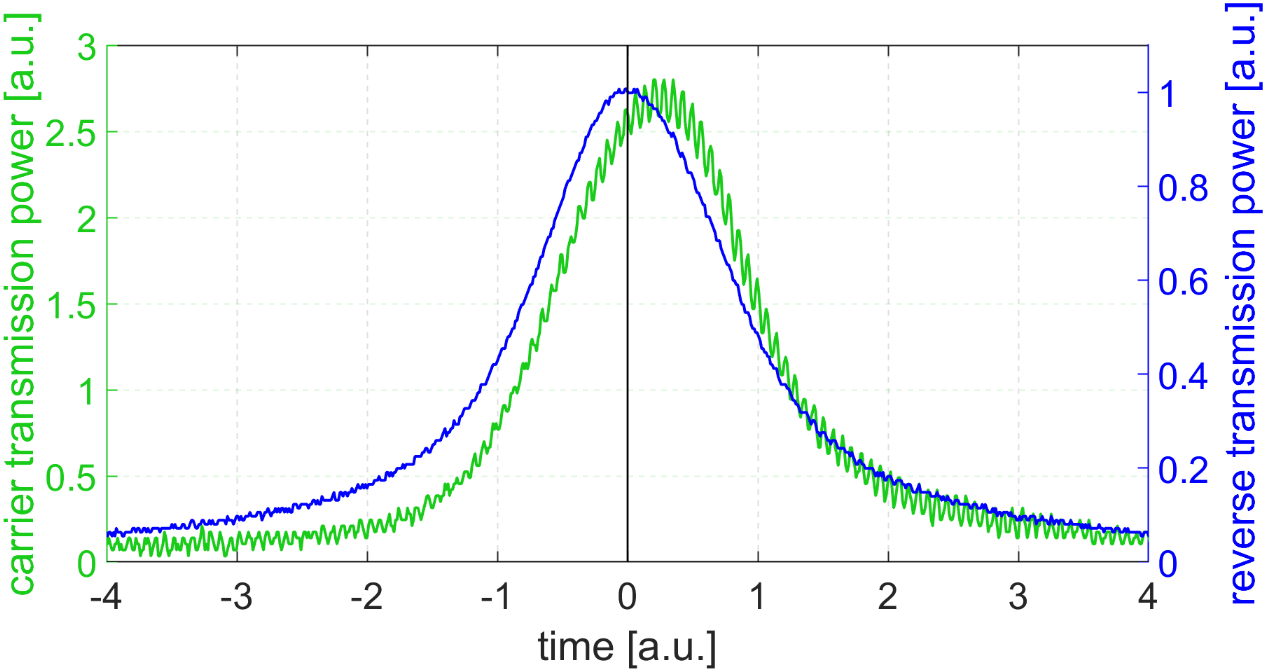
The circulating power increases by a factor of **19** and the signal is amplified by a factor of **1.4**. With the OPO crystal inserted, the finesse was reduced to ~100 (clipping loss).

# Signal amplification experiment



OPO cavity

## (3) With OPO; 50mW input



The circulating power increases by a factor of **2.7** and the signal is amplified by a factor of **1.1**. The reduction of the amplification gain is caused by a shortage of pump power.

# Prospects to observe the optical spring

| OPO | mass | oscillator | finesse | input power | opt spring |
|---|---|---|---|---|---|
| no | 210mg | 10Hz PET | 400 | 120mW | 100Hz, observed |
| no | 210mg | 10Hz PET | 1000 | 140mW | 250Hz, observed |
| no | 280mg | 10Hz PET | 300 | 570mW | 140Hz, observed |
| yes | 280mg | 10Hz PET | 100 | 10mW | estimated to be 5.2Hz |
| yes | 280mg | 35Hz BeCu | 100 | 0.6mW | estimated to be 1.3Hz |

The BeCu suspension is stable enough to see the difference larger than $0.03\ \mathrm{Hz}$. $\sqrt{35.7^2 + 1.3^2} = 35.72\ \mathrm{Hz}$ is not good enough but a factor of 2 improvement in the total gain will let us see the shift of the optical spring frequency.

We plan to implement the green cavity to increase the gain.

# Summary and discussions

- We succeeded in observing an optical spring in the transfer function measurement of a detuned FP cavity.
- We tried to see the optical spring with an intracavity OPO inserted in the FP, but have not succeeded.
- The signal amplification gain is measured to be 1.4 but the input power is limited to ~1mW as the carrier starts to oscillate in the OPO.
- We have replaced the PET suspension by the BeCu one so that a small difference of the optical spring can be found.