



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

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## 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)



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

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



# 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



### Verification in transfer function



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





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#### **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)



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# Observation of optical spring (without OPA)



$$\phi \simeq 10 \deg, f_{os} \simeq 8.7 \text{ Hz}$$

$$\phi \simeq 8 \deg, f_{os} \simeq 10.5 \text{ Hz}$$

$$\phi \simeq 6 \deg, f_{os} \simeq 11.8 \text{ Hz}$$

 $\phi$ : detuning angle

• Solid: fit with 
$$H_{OS}(\omega)$$

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







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







- 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



- 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



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