Photothermal and nonlinear optical effects in the signal amplification system

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2022/11/17

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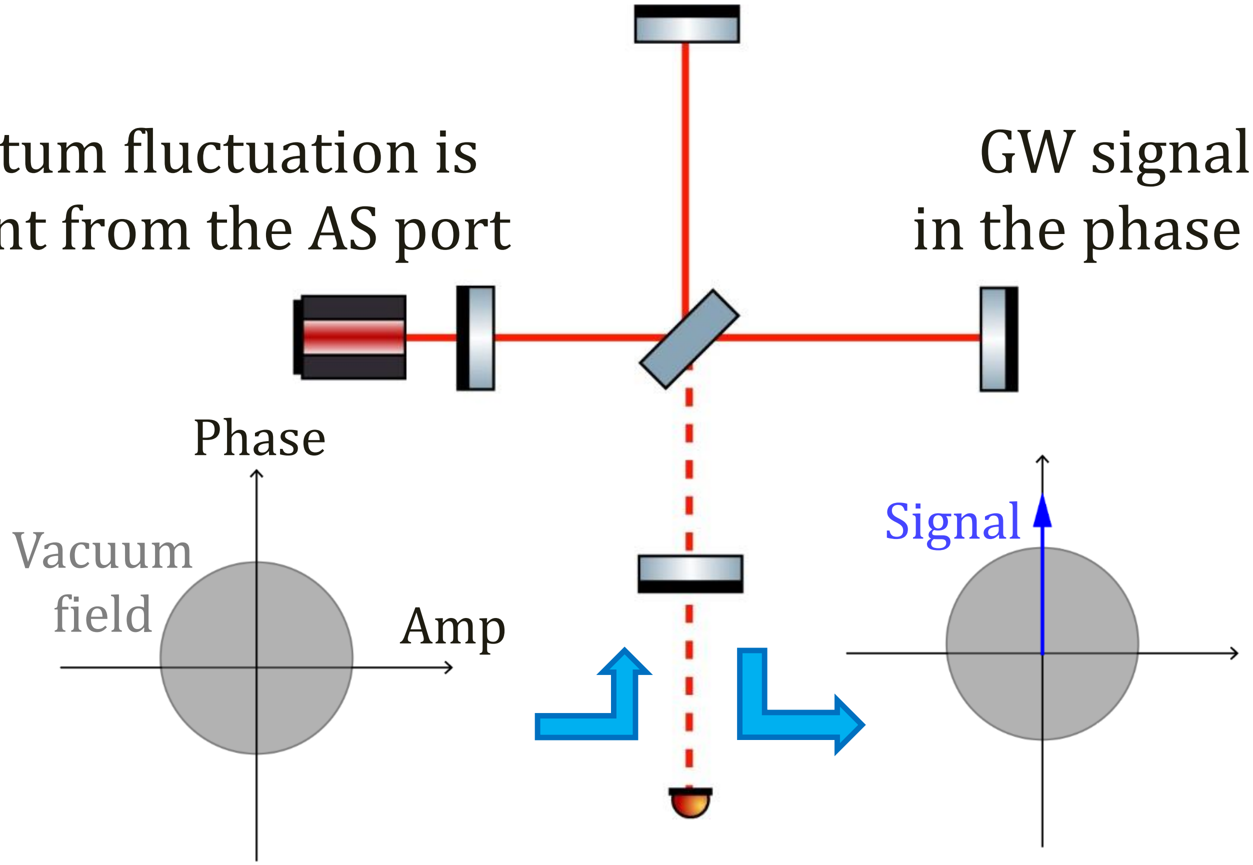
Quantum Noise in the GW Detector

Sensitivity = Signal/Noise

Principle sensitivity is determined by the quantum fluctuation

Quantum fluctuation is incident from the AS port

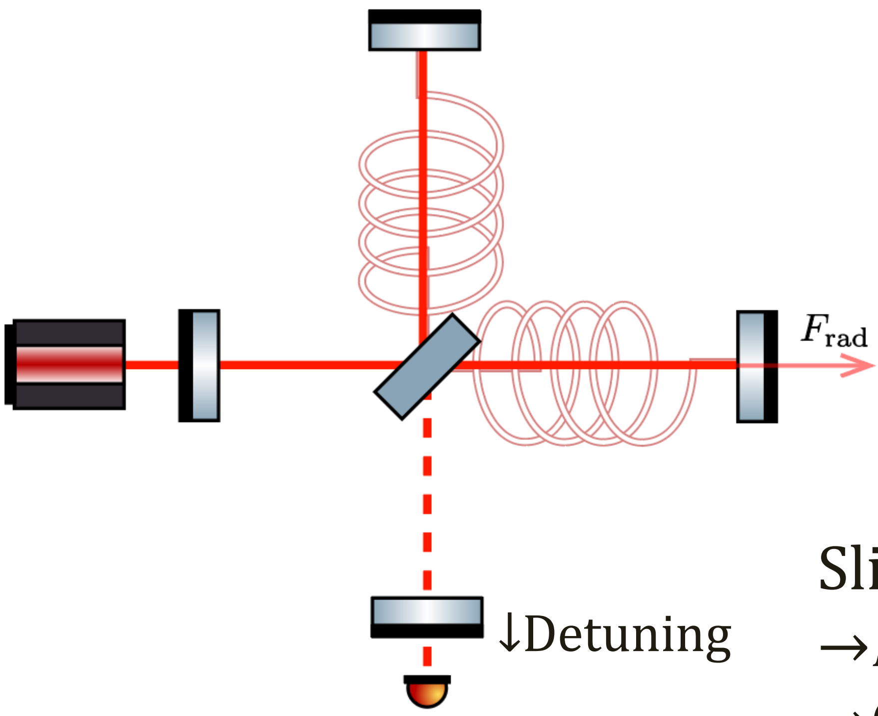
GW signals appear in the phase quadrature

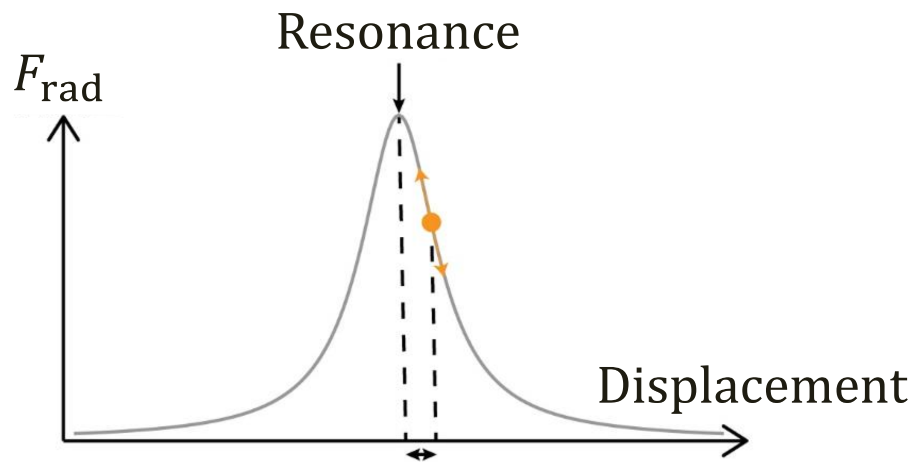


Improve sensitivity → Signal amplification and/or noise reduction

Improve Sensitivity: Optical Spring

End mirrors receive radiation pressure force F_{rad}
→Amplify GW signals by a spring composed of light





Slightly detuned from the resonance
→F_{rad} is proportional to displacement
→**Generate optical spring**

Amplify the GW signals around resonance frequency
Resonance frequency is limited by laser power, ~100 Hz for KAGRA

Improve Sensitivity: Squeezing

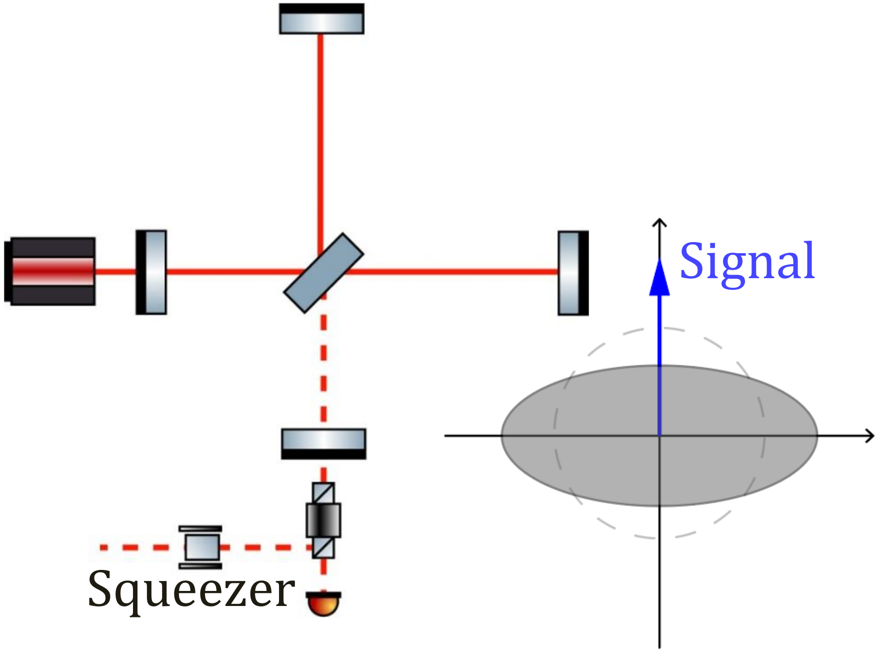
Vacuum field is elliptically deform by the squeezer

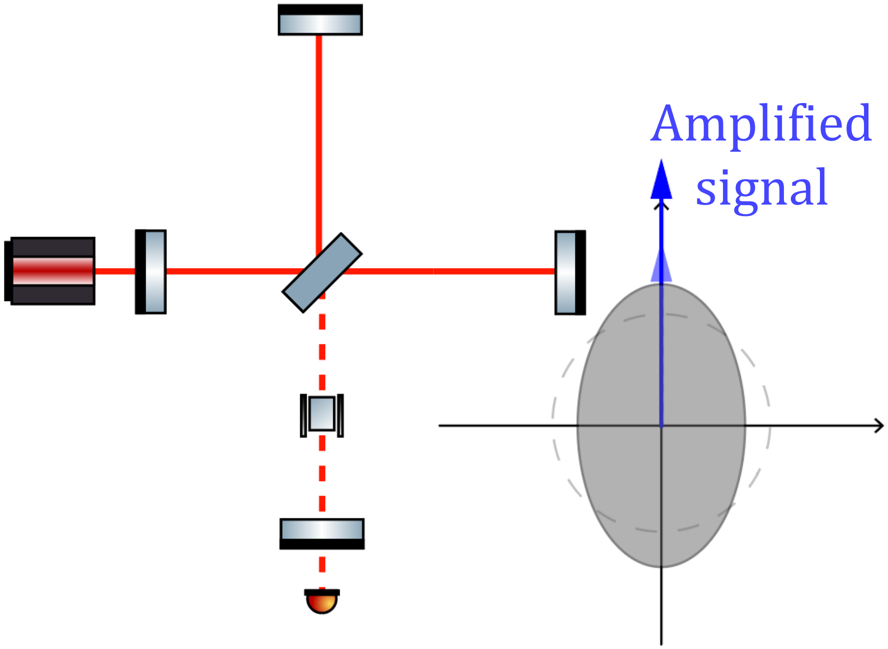
Input squeezing

- Input vacuum field is squeezed
- Already installed in GW detectors

Intracavity squeezing

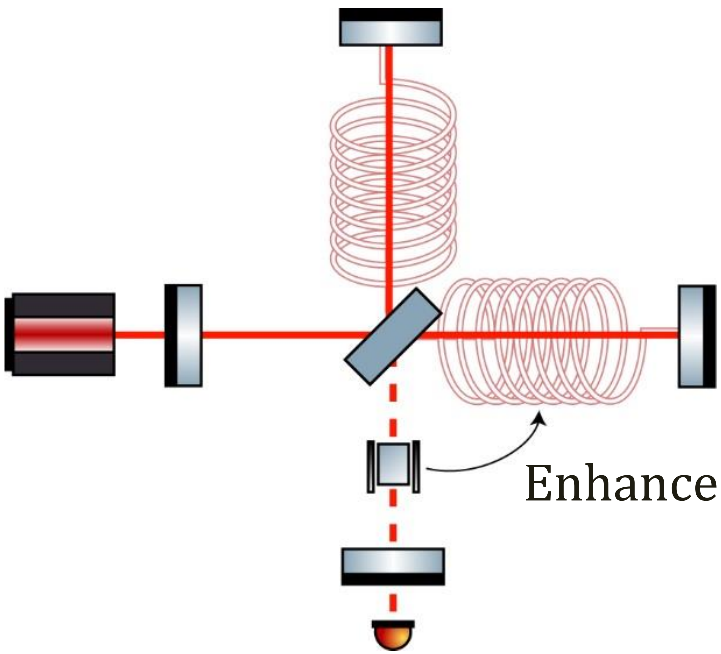
- Signal and noise amp rates are different
- Principle verification experiments is required

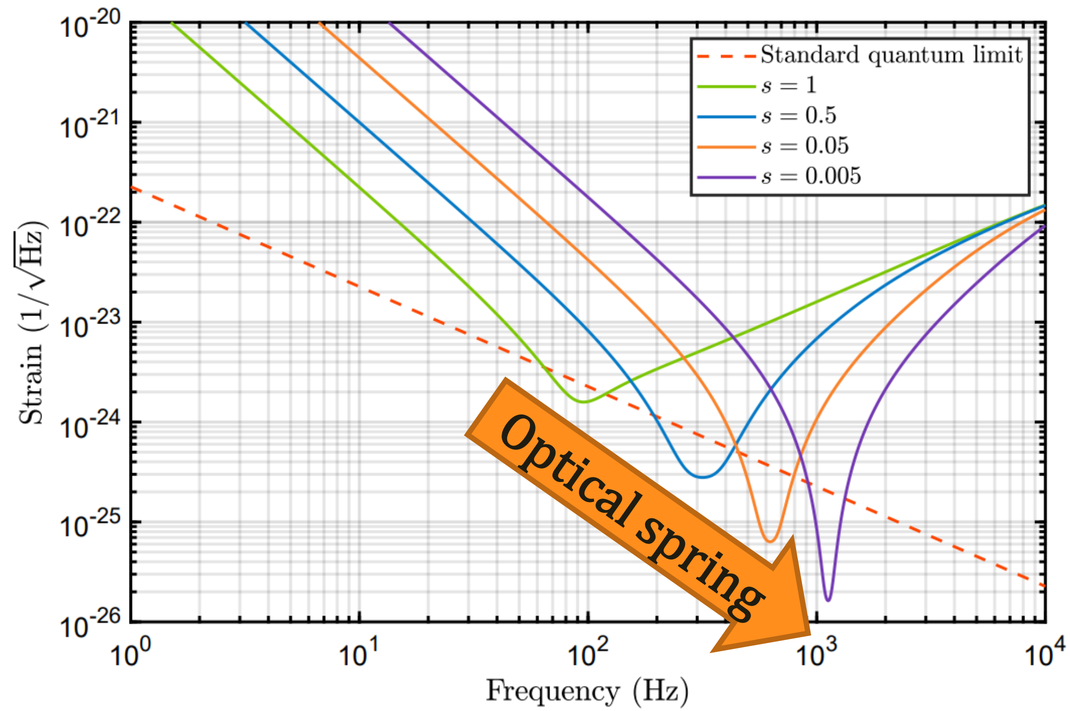




Signal Amplification System

Our proposal: enhance optical spring by the intracavity squeezing





Resonance frequency of the optical spring is shifted to high frequency band with strong intracavity signal amplification

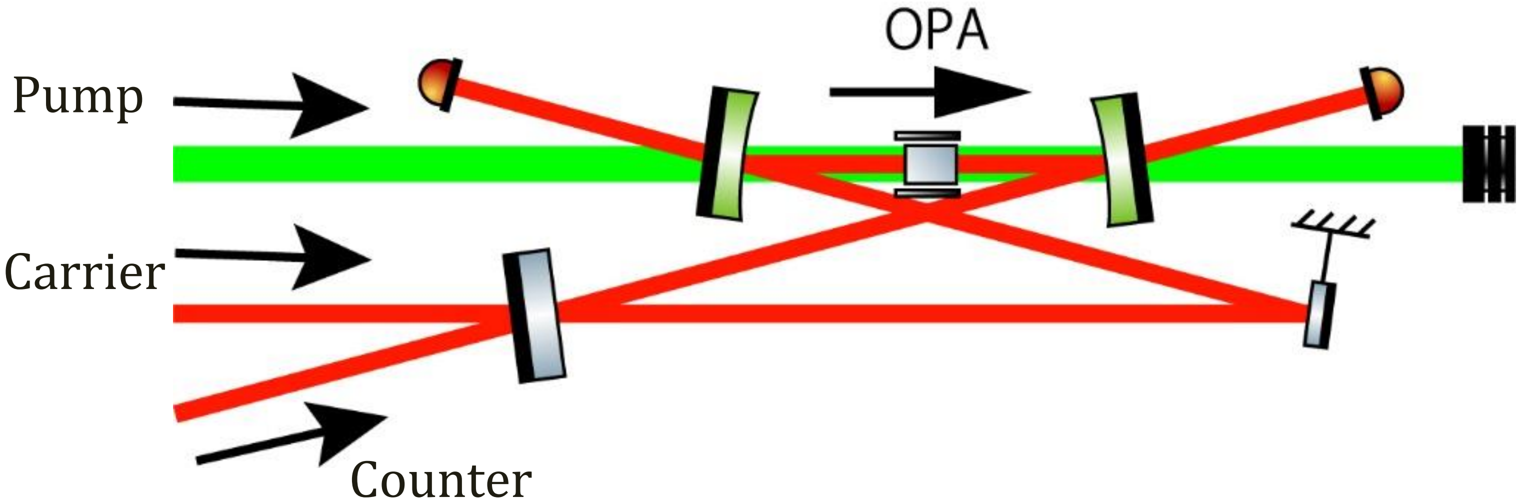
→**<u>Amplify ~kHz GW signals such as BNS or supernova</u>**

OPA Experiment

Experimental goal:

Observe an optical spring enhanced by intracavity signal amplification

Intracavity signal amplification can be implemented with optical parametric amplification (OPA)



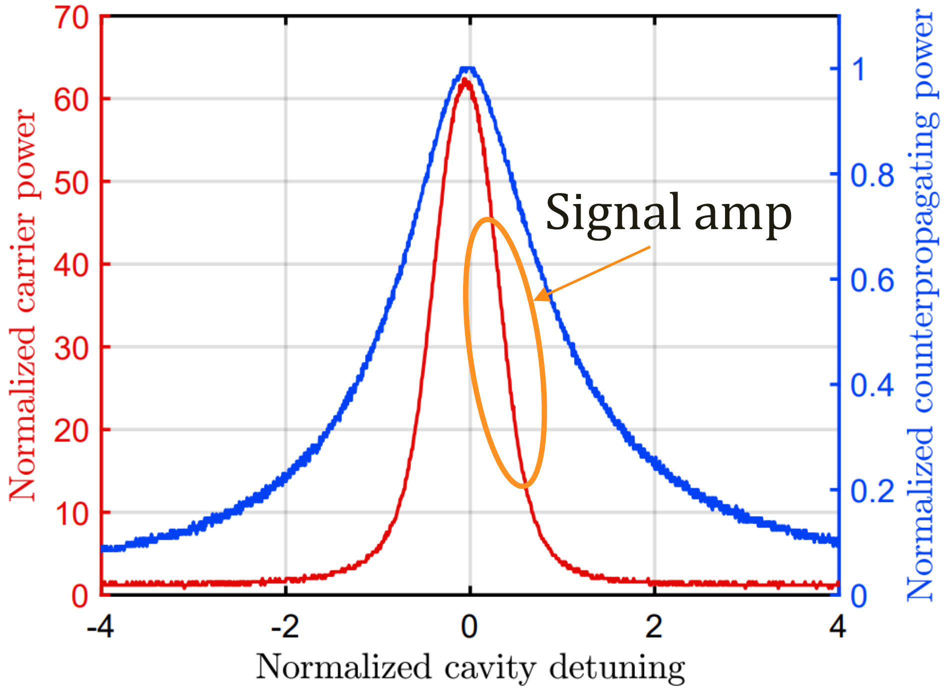
Amplify carrier light (1064 nm) by pump light (532 nm)

Incident carrier light and counterpropagating light

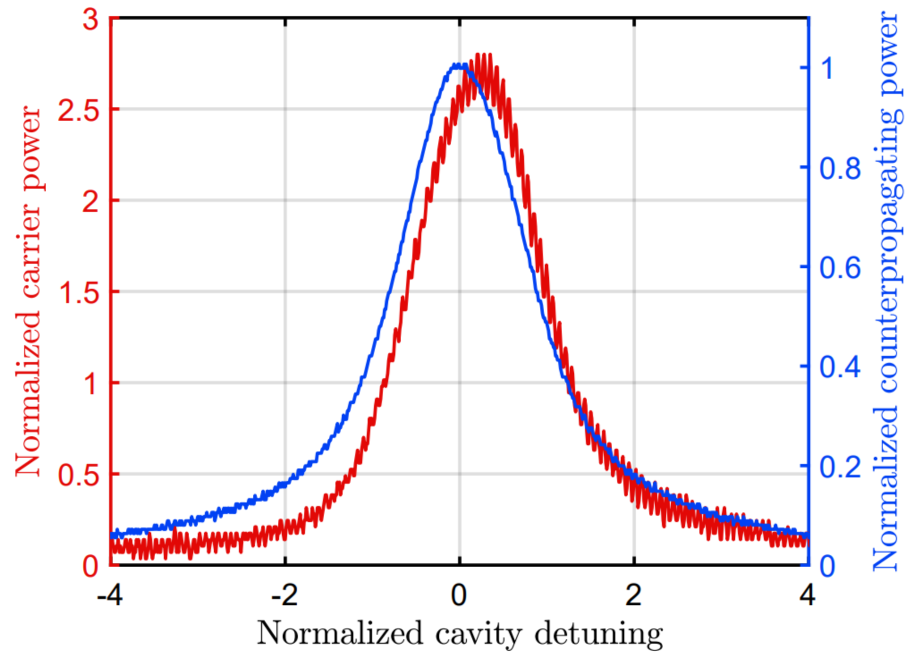
→Compare amplified light and non-amplified light

Power and Signal Amplification

Measure the transmission power from cavity scan



Incident 0.5 mW carrier
Power amp gain：62
Signal amp gain：1.62



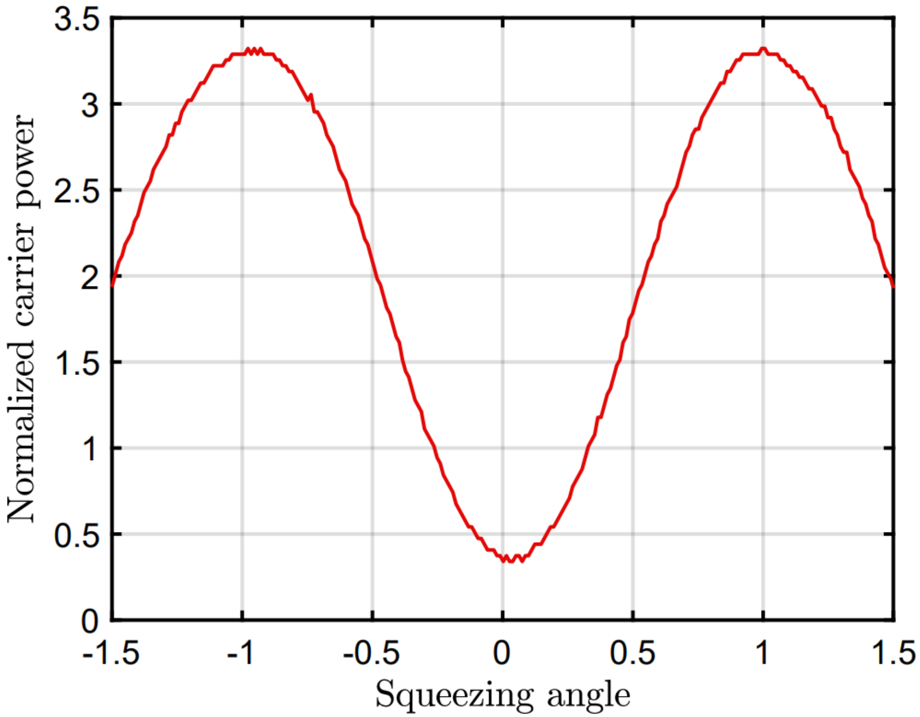
Incident 50 mW carrier
Power amp gain：2.7
Signal amp gain：1.08

Intracavity carrier power becomes as high as pump power
→ OPA process is suppressed

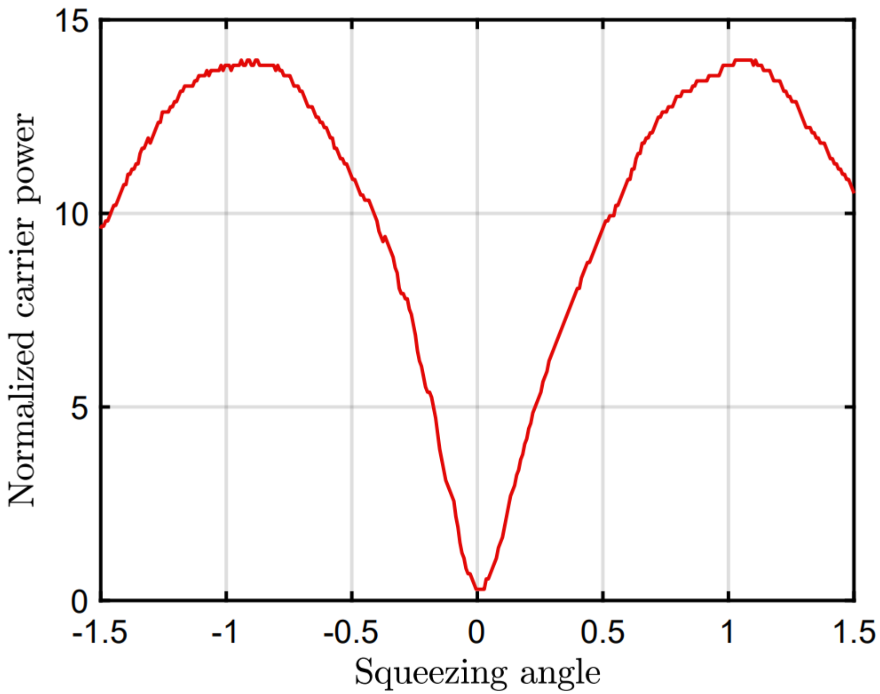
OPA Near the Threshold

Cannot incident high power carrier→Need high gain OPA

Low gain OPA
→Sin wave (consistent with theory)



High gain OPA
→Sin wave is distorted



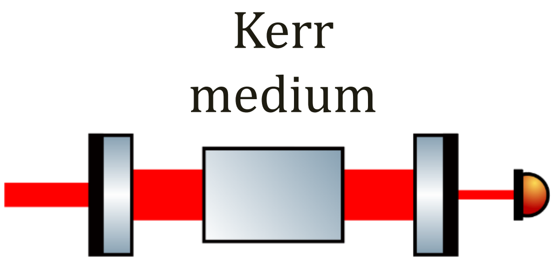
Incident 4 mW carrier

Normalized cavity detuning $\simeq 1/\sqrt{3}$

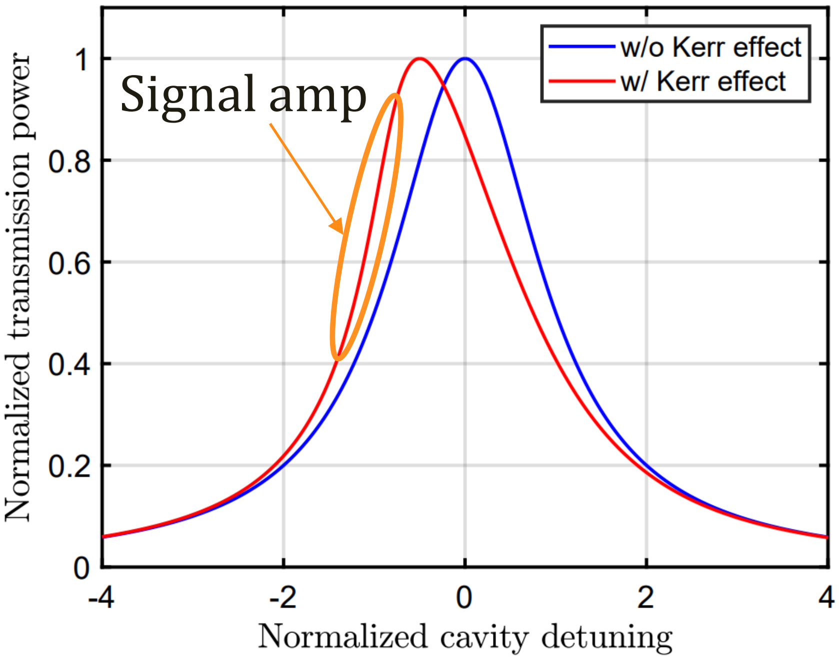
OPA process is not maintained
→Cannot observe enhanced optical spring

Kerr Effect

OPA is not the only way to produce signal amplification
→Focusing on the optical Kerr effect; a phenomenon in which the refractive index changes in proportion to light intensity



Strong power→Strong Kerr effect
→**Increase input power and signal amp gain!**

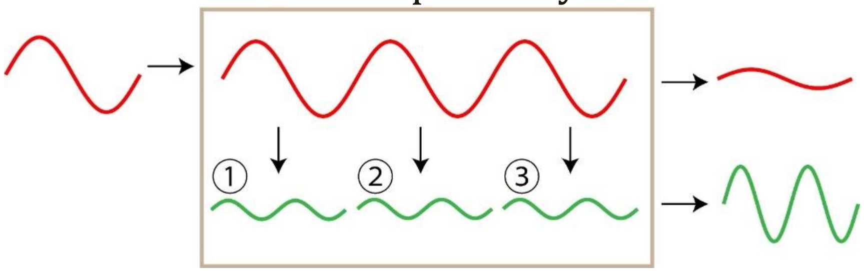


The usual Kerr effect requires extremely high intensity……
e.g. ultrashort pulsed light in an optical fiber
→It can be achieved by simply setting the <u>phase mismatch condition</u>

Cascaded Nonlinear Optical Effect

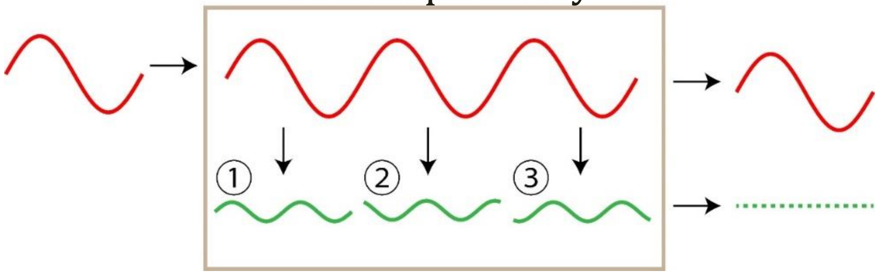
Phase matching: match the speed of different frequency light propagating through a nonlinear optical crystal

Phase-matching condition



→Secondary harmonic generation occurs

Phase-mismatching condition



→It's **NOT** just the infra-red light propagating

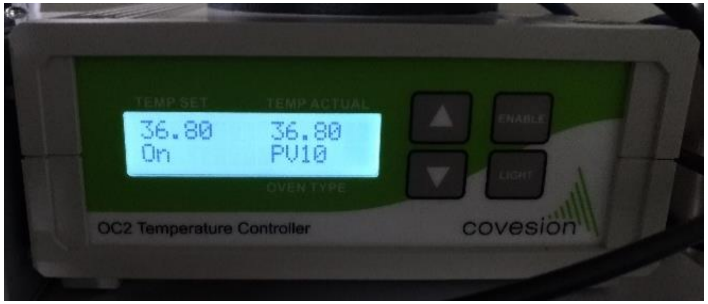
The phase of the entire infra-red light changes as the generated green light is reconverted to the infra-red light

→ The effective refractive index changes (**equivalent to Kerr effect**)

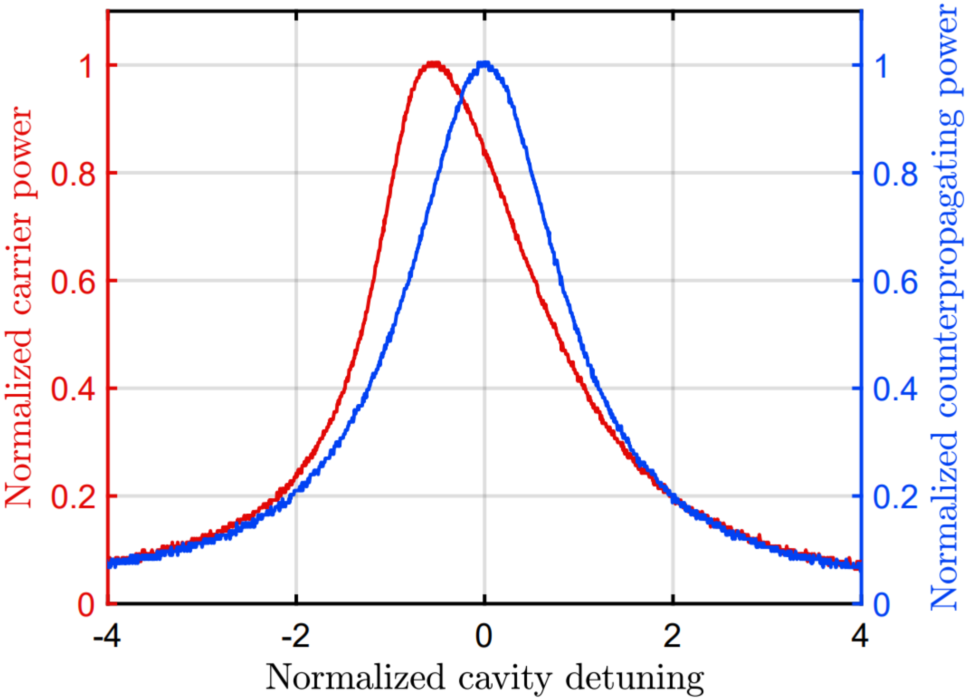
Confirmation of the Kerr Effect

Phase-mismatching condition can be achieved by changing the temperature of the crystal

Temperature controller



Phase-matched at 36.8℃
Phase-mismatched at 42.0℃

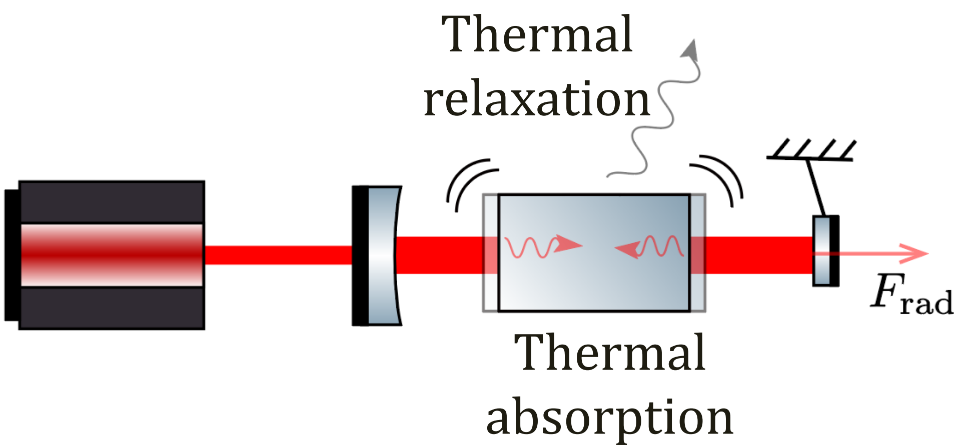


Carrier: 570 mW   Counter: 14 mW

Achieved about 1/3 of the critical Kerr effect
→Sufficient to observe the enhanced optical spring!

Photothermal Effect

- Kerr effect requires relatively high intracavity power (~40 W)
- Nonlinear optical crystal has relatively large thermal absorption and thermal expansion coefficient
→Photothermal effect cannot be neglected

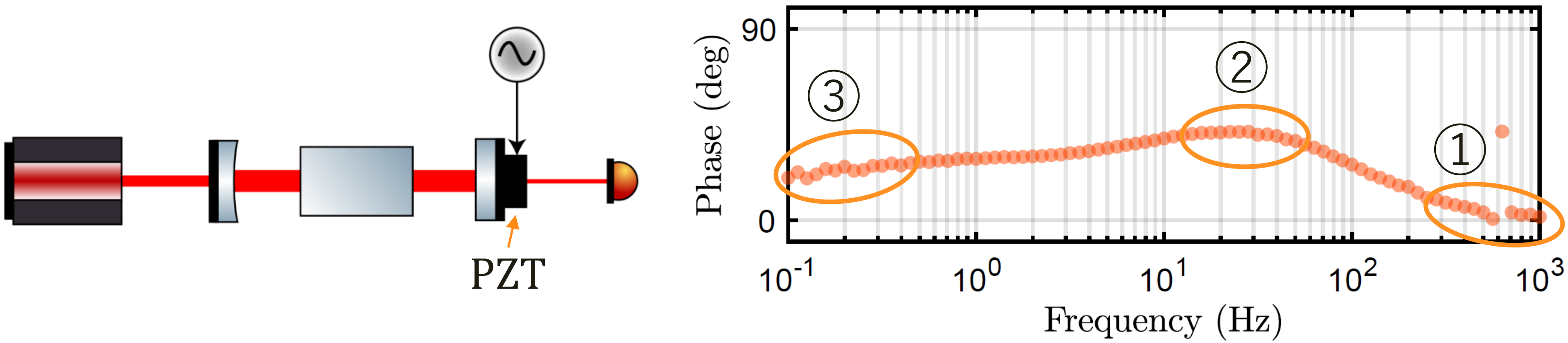


Crystal temperature changes
→Thermal expansion occurs
→Cavity length changes
→Cavity property modified

Consider the impact of the photothermal effect on the radiation pressure force F_{rad} and optical spring constant

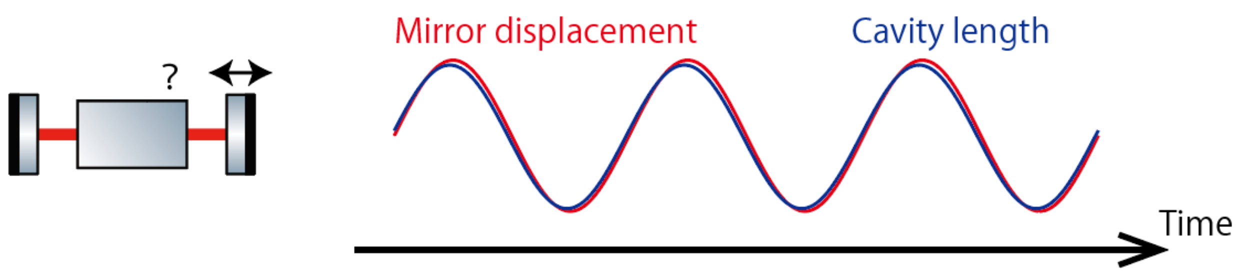
Frequency Response of the Cavity

Measure the frequency response of the cavity



Focus on rates of the photothermal effect

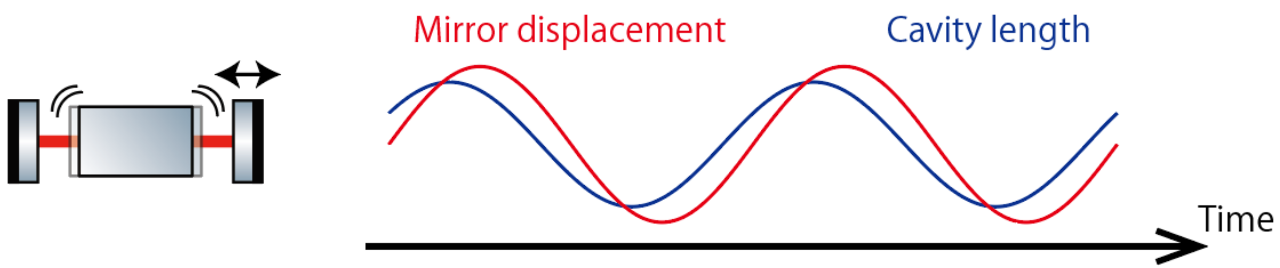
①Frequency larger than the photothermal absorption rate



→Not affected by the photothermal effect because
the signal is reversed before thermal expansion occurs

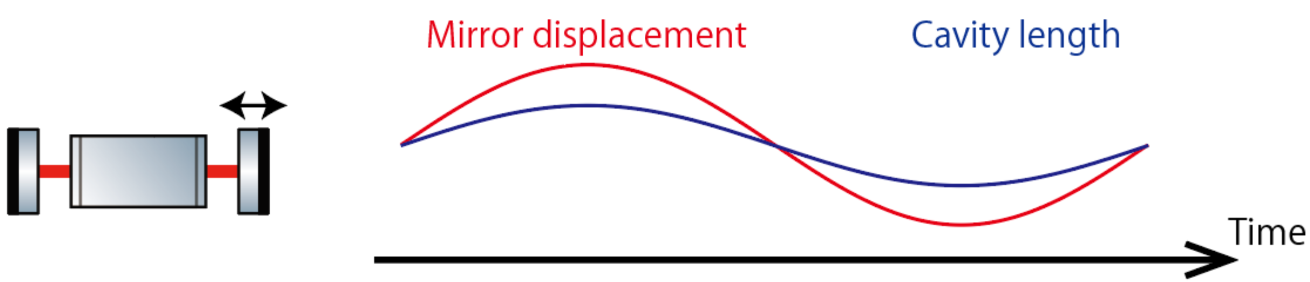
Qualitative Explanation

②Frequency as high as the photothermal absorption rate



→Cavity length stored by thermal expansion is released
→Cavity length changes faster than signal (phase lead)

③Frequency lower than the photothermal relaxation rate



→Crystal reaches the thermal equilibrium
→Cavity length changes following the signal (phase unchanged)

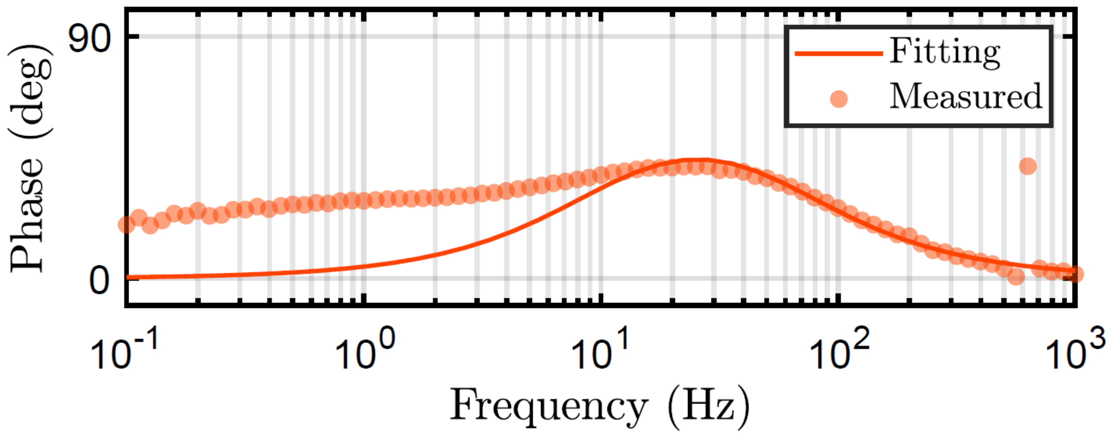
Frequency Response of the Cavity

The relationship between the cavity length x and the mirror displacement x_{act} can be written as:

$$\frac{x(\Omega)}{x_{\mathrm{act}}(\Omega)} = \frac{\gamma_{\mathrm{th}} + i\Omega}{(\omega_{\mathrm{th}} + \gamma_{\mathrm{th}}) + i\Omega}$$

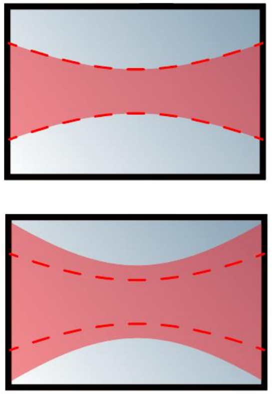
Photothermal absorption rate

Photothermal relaxation rate



High freq band

Low freq band



The area contributing to the photothermal effect is expanded in the low-frequency band → It agrees with theory above 15 Hz

Optical Spring with Photothermal Effect

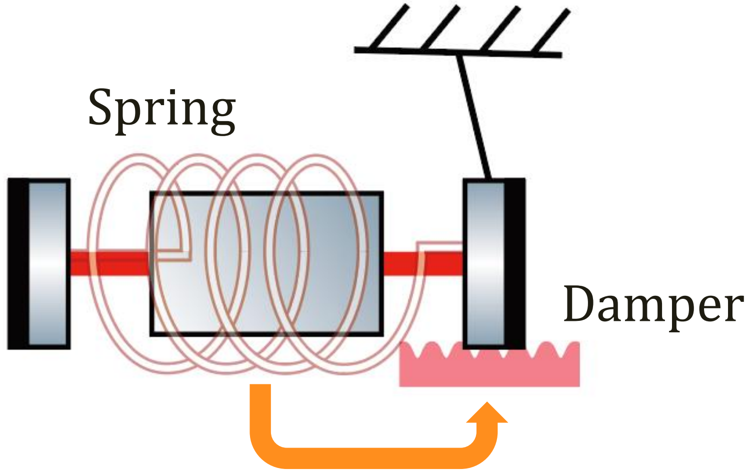
Optical spring constant can be written as:

Radiation pressure force → $F_{\mathrm{rad}}(\Omega) = -k_{\mathrm{opt}} x(\Omega)$ (Optical spring constant: k_{opt}; Cavity length: $x(\Omega)$)

This relationship does not change in the presence of photothermal effect, but the cavity length and mirror displacement do not match:

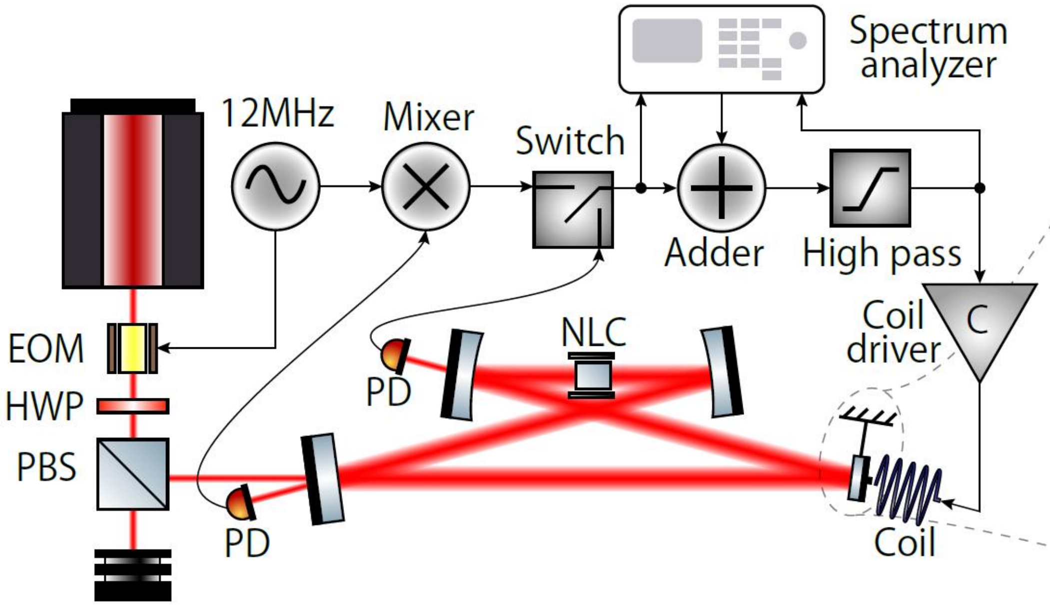
$$F_{\mathrm{rad}}(\Omega) = -\frac{\gamma_{\mathrm{th}} + i\Omega}{(\omega_{\mathrm{th}} + \gamma_{\mathrm{th}}) + i\Omega} k_{\mathrm{opt}} x_{\mathrm{act}}(\Omega)$$

New optical spring constant
has a large imaginary component
→**Photothermal effect provides extremely significant optical damping**



Experimental Setup

Apply a signal to the coil magnet actuator and detect the response
→Measure susceptibility of the optomechanical oscillator

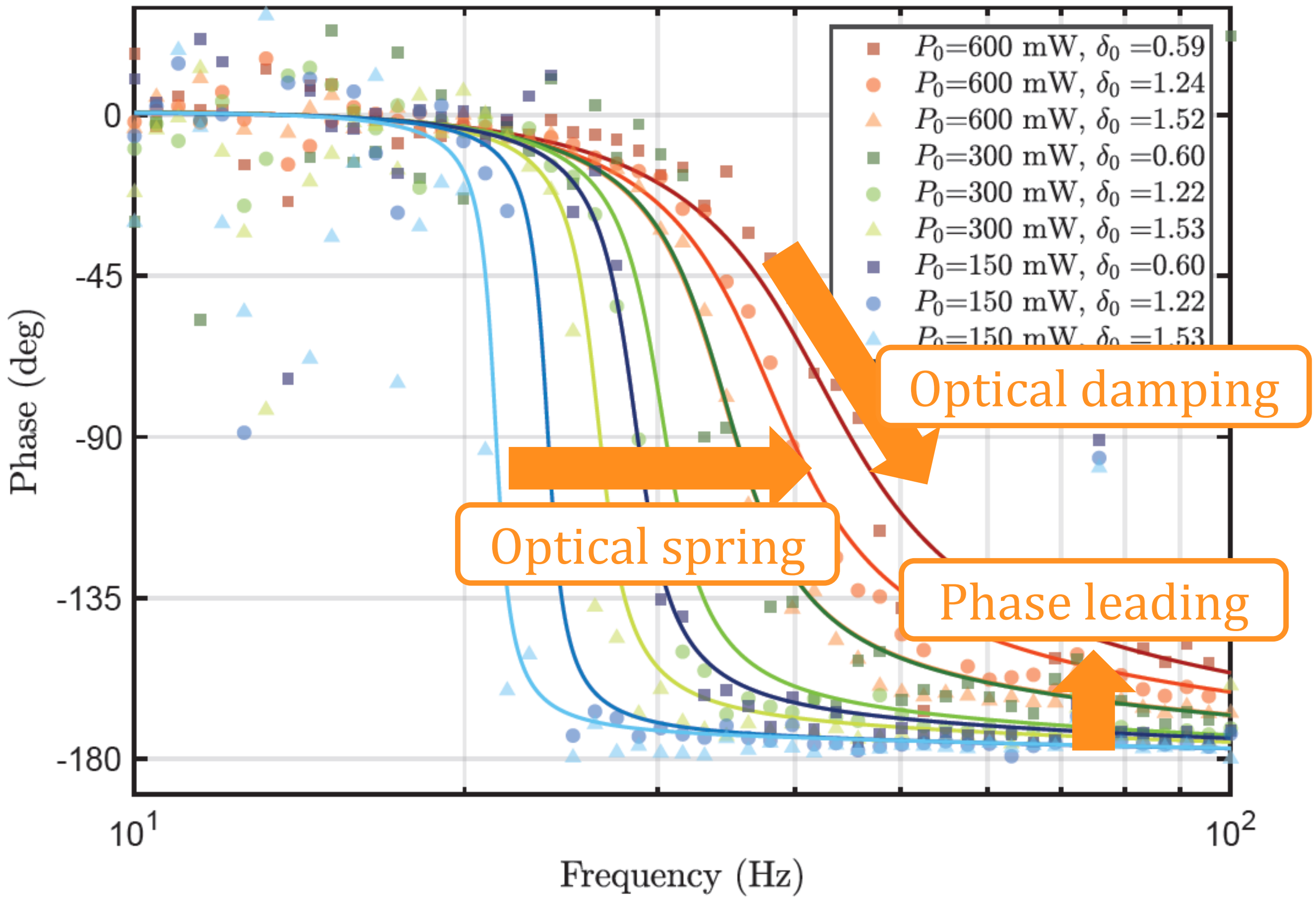


NLC was heated to 120°C
→Nonlinear optical effects can be negligible

Resonance frequency: 14.2 ± 0.1 Hz
Mechanical Q factor: 193 ± 3

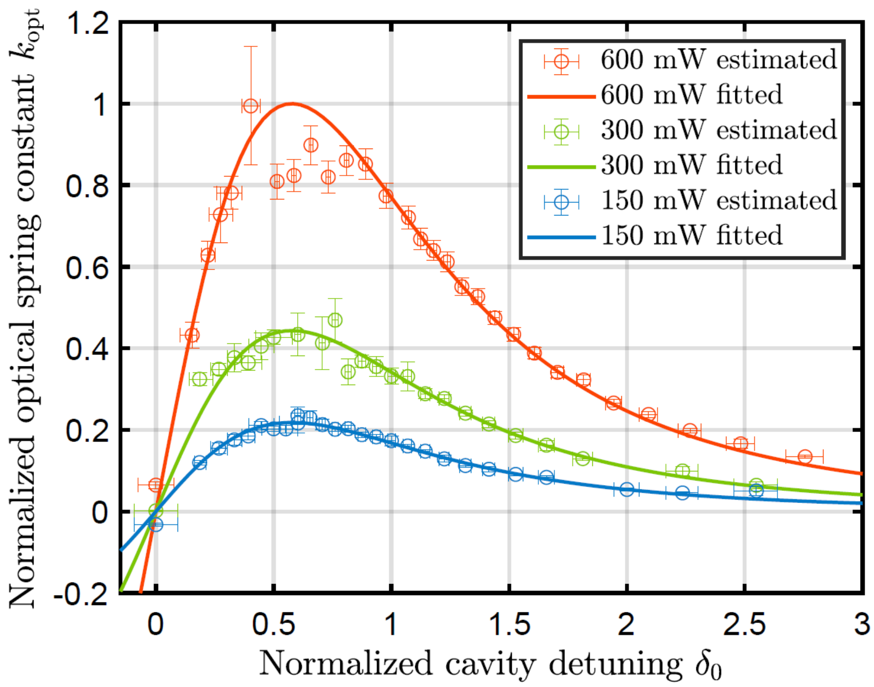
Transfer Function of the Optical Spring

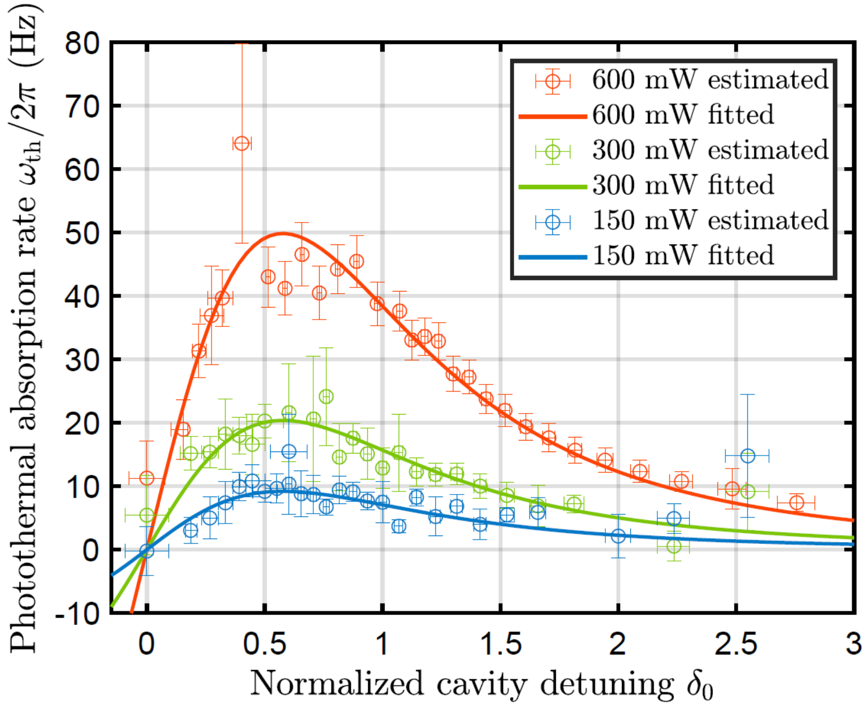
Large input power P_0 and small cavity detuning δ_0
⇒Large optical spring constant k_{opt} and
large photothermal absorption rate ω_{th}



Estimation Results

Estimate two parameter from phase measurements





Precisely estimate k_{opt} <u>in the absence of photothermal effects</u>

→Virtually eliminate the influence of photothermal effects!

Why are k_{opt} and ω_{th} the same function?

Equivalency

Radiation pressure force is proportional to the intracavity power:

$$F_{\mathrm{rad}} \sim P \sim k_{\mathrm{opt}} x$$

Radiation pressure force → F_{rad}; Intracavity laser power → P; Optical spring constant → k_{opt}; Cavity length → x

Photothermal absorption rate is the value of how much the heat absorption amount changes with the cavity length change:

$$W \sim P \sim \omega_{\mathrm{th}} x$$

Heat absorption amount → W; Photothermal absorption rate → ω_{th}

→k_{opt} and ω_{th} are **identical** except for the proportionality factor

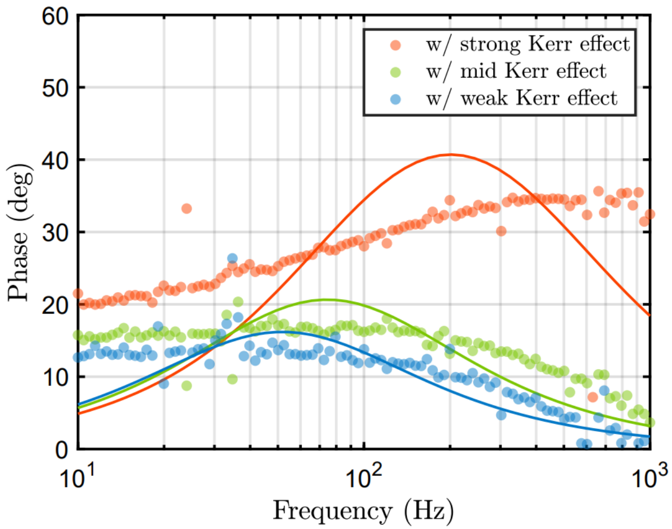
→**They exhibit the same functional dependencies for all parameters**

→It is impossible to avoid the photothermal effect

Need to design interferometers to incorporate photothermal effects

Phase Measurement Results with Kerr Effect

Intracavity signal amplification enhance optical spring constant k_{opt} and photothermal absorption rate ω_{th} by the same factor

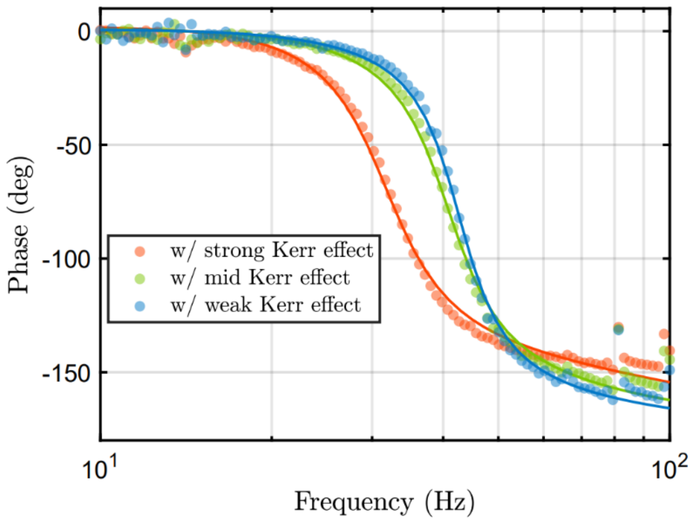


- Frequency response of the cavity

Kerr effect may be enhancing the photothermal absorption rate,
but not consistent with the fitting

- Transfer function of optical spring

Kerr effect seems to reduce the optical spring constant…
This tendency is opposite to the theoretical prediction



Summary

- The sensitivity of GW detectors can be improved by optical spring and/or squeezing technique
- The resonance frequency of optical spring can be enhanced by intracavity signal amplification
- Kerr scheme provide both high intracavity power and high signal amplification rate
- Photothermal effect is NOT just a technical problem, but also an essential property of signal amplification system
- Further experiments needed to investigate coupling between Kerr effect and photothermal effect