Parametric amplification for a stiff optical spring

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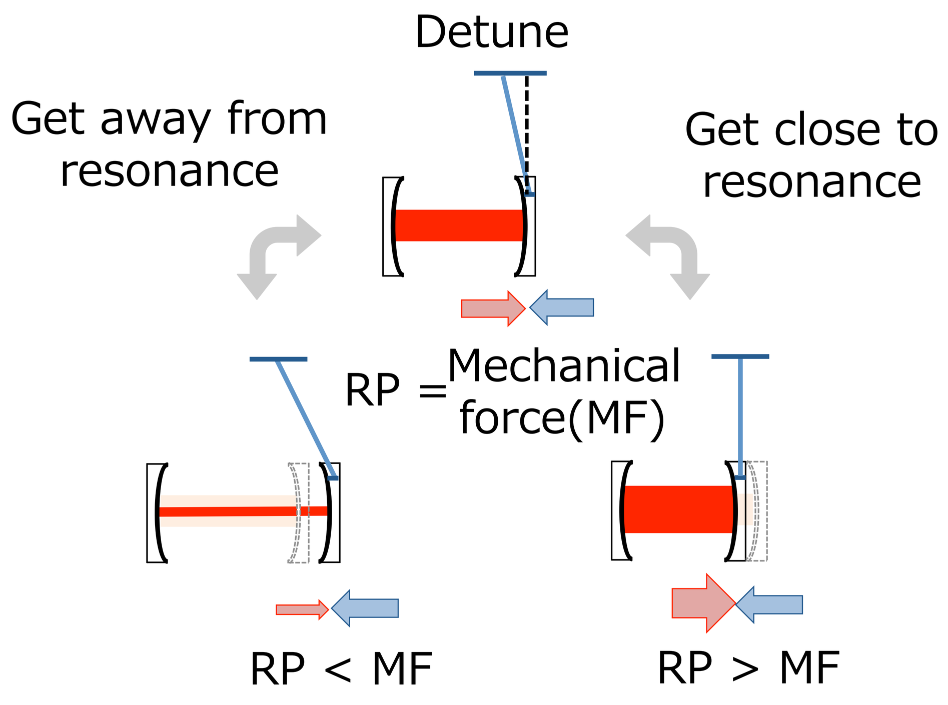
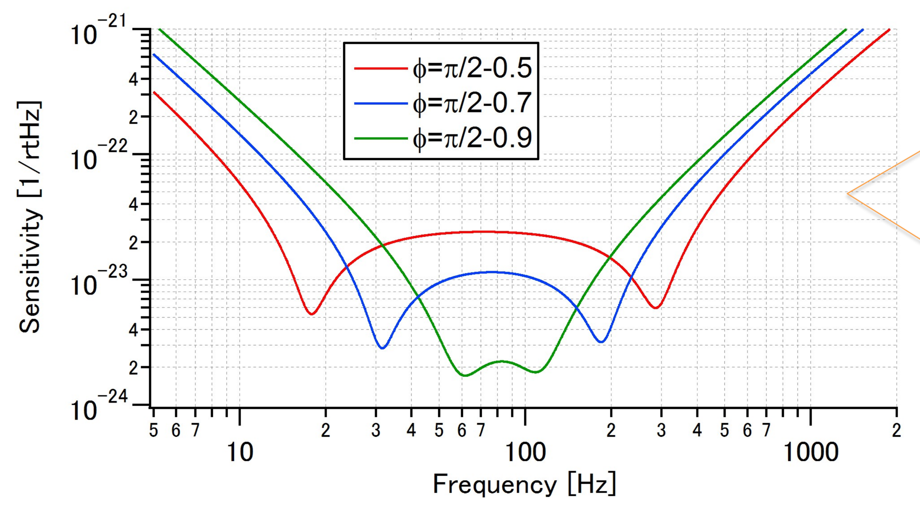
Motivation We want to shift the optical spring resonance to higher frequency, where many interesting astronomical sources are expected and the quantum noise only limits the sensitivity.

Optical spring

Optical spring is generated when the cavity is detuned from a resonant point. If the mirror goes away from the operating point, the mirror comes back to the prior position, where the radiation pressure and mechanical force are balanced. As the detune phase changes, the frequency gap of two dips changes. Note that the shift of the lower dip is limited by the upper dip, whereas the detune phase is chosen.





Lower dip
the optical spring resonance.

Upper dip
the optical resonance of the coupled cavity with the detuned SRC and the arm cavity.

Optical spring resonance

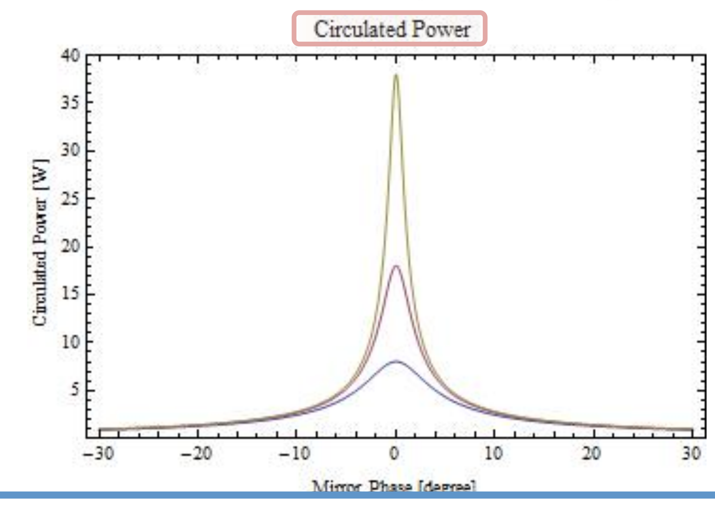
Optical spring resonance is determined by the formula below.
(High cavity pole approximation)

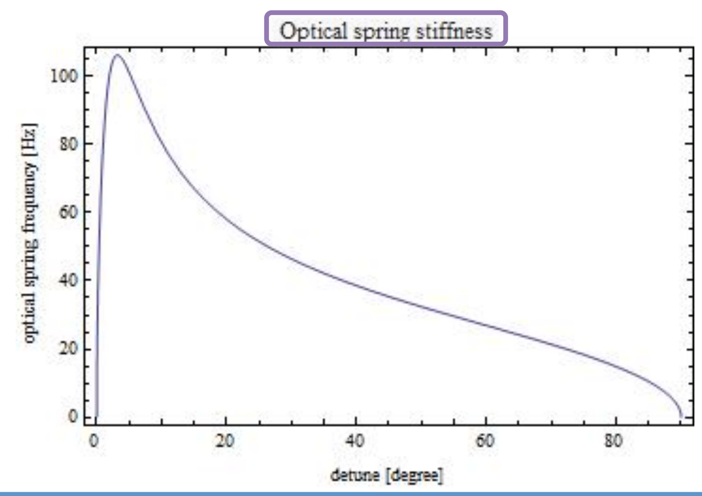
$$f_{os} \propto \sqrt{\frac{2I_0}{m}\frac{1}{\left(r+\frac{1}{r}-2\cos2\phi\right)}\sin2\phi}$$

I_0: laser power
m: mass of the mirror
r: reflectance of the mirror
φ: detune phase

Red term
– the amplification of the cavity
Purple term
– the amount of the amplitude signal

Optical spring resonance cannot exceed a certain frequency just by changing the detune phase.





Improvement of the detection band — Stiff optical spring

In order to realize a stiffer optical spring, two methods are known : to increase the laser power and to change the detune phase. However these conventional methods have some weak points.

High power laser	Induces the thermal noise on the mirror. Technically hard to keep high power stable.
Change the detune phase	Limited by the optical resonance frequency.

Based on these points, we suggest a signal amplification to realize the stiff optical spring without the high power laser.

Shift of the optical spring resonance

$$f_{os} \propto \sqrt{\frac{2sI_0}{m}\frac{1}{\left(r+\frac{1}{r}-\left(s+\frac{1}{s}\right)\cos2\phi\right)}\sin2\phi}$$

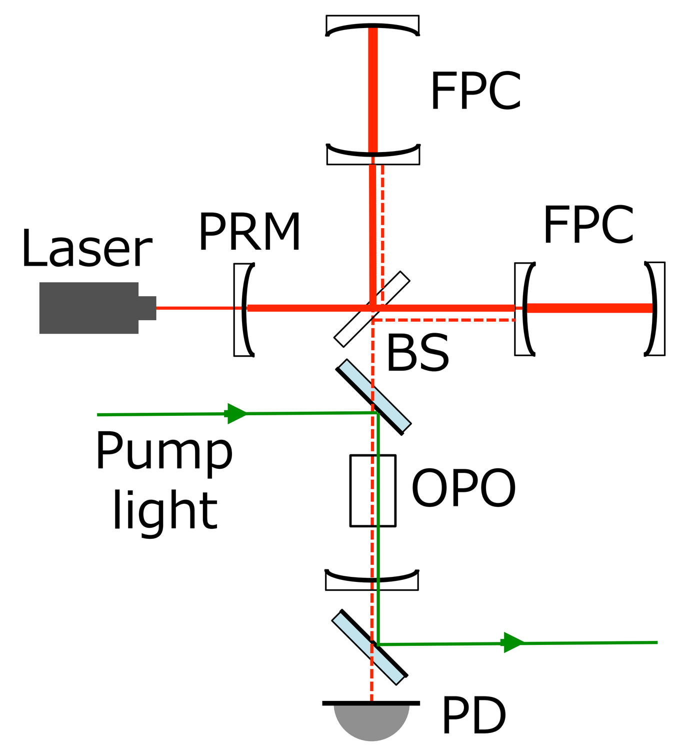
s: squeezing factor

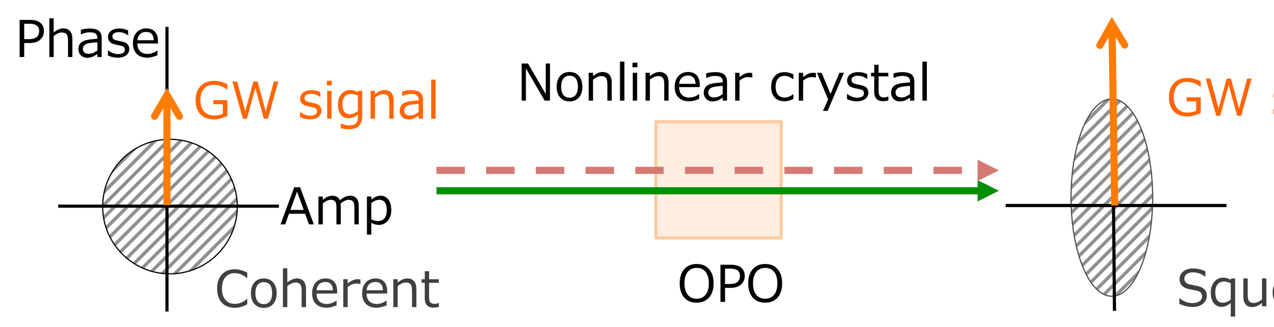
Green term – the effectively laser power.
Orange term – intra-cavity squeezing coefficient

Optical spring with signal amplification exceed a certain frequency by changing the squeezing factor.

Signal amplification

In order to realize the signal amplification, we use the OPO (Optical parametric oscillator) which consists of the nonlinear optics and pump light. It is placed inside the SRC. While, the OPO is typically used for reduction of the phase fluctuations, we use the OPO for signal amplification. Signal amplification has similar effects as using the high power laser.



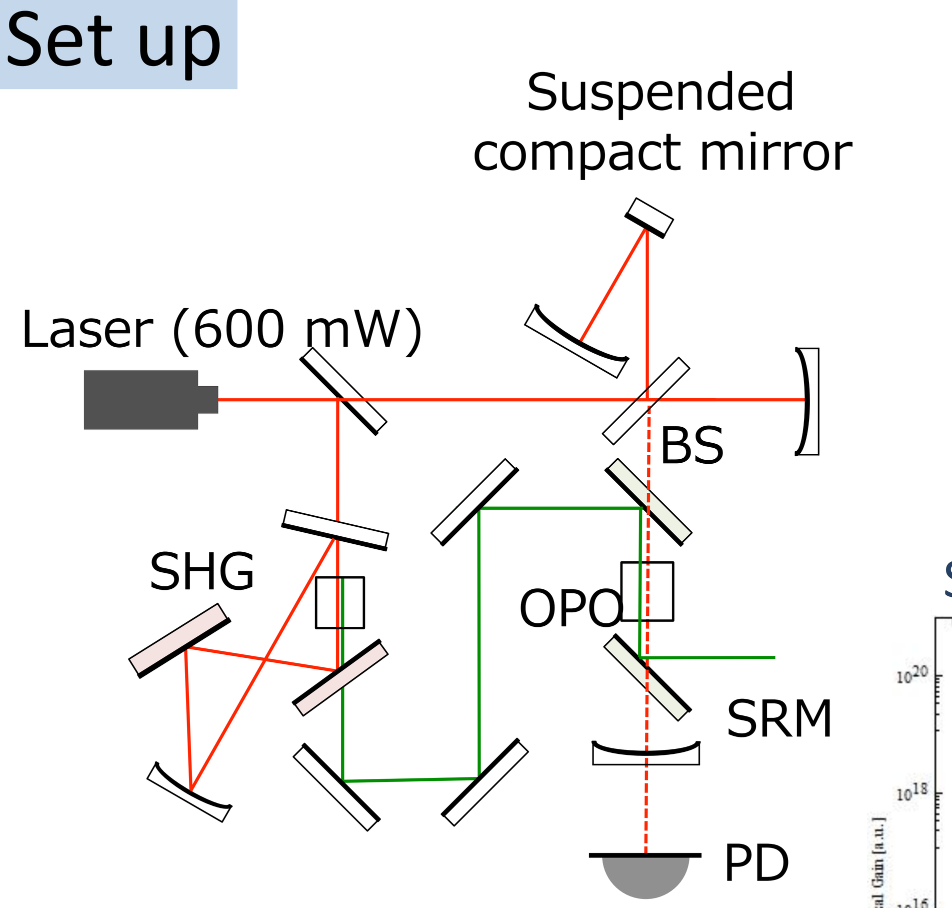


OPO : Optical parametric oscillator

: Pump light ($2\Omega_0$)
: Carrier light (Ω_0)
Ω_0 : Frequency

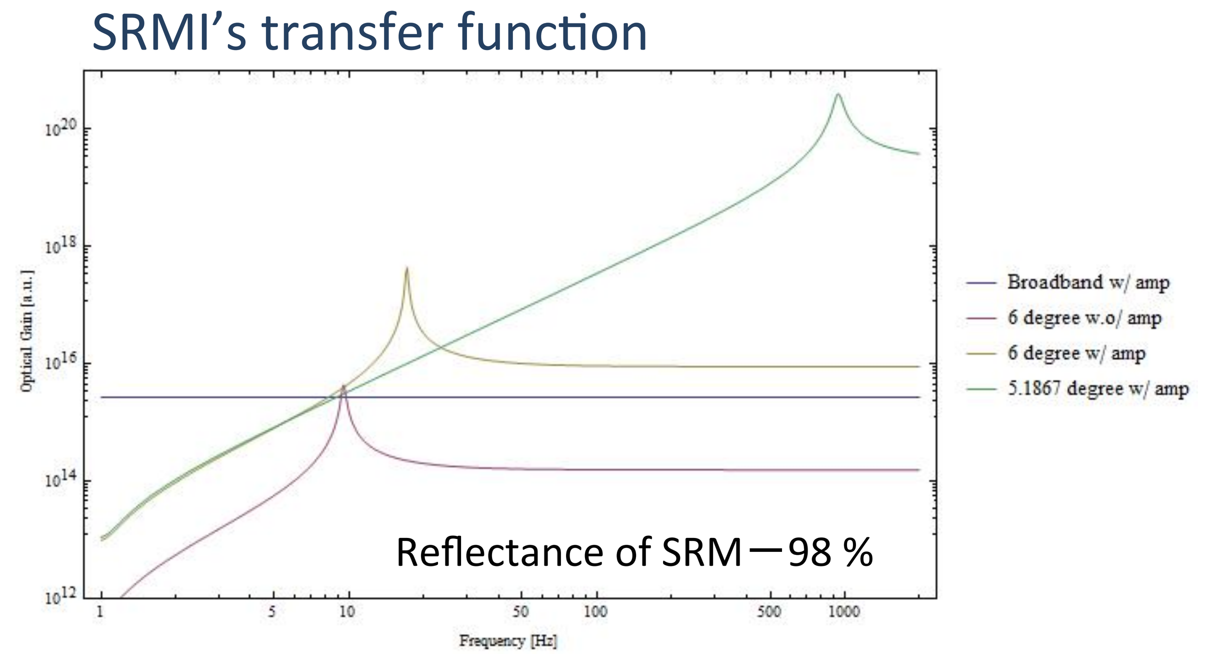
Experiment

Set up



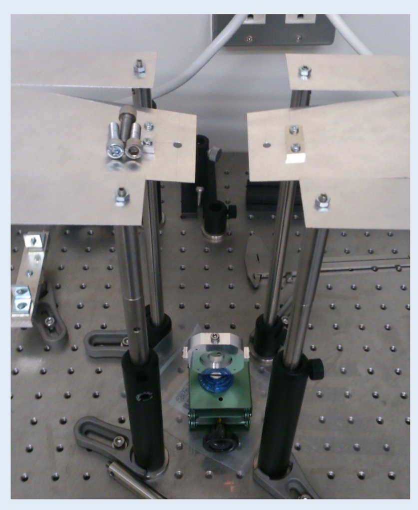
MI — locked
SRC — locked
SHG — constructing
OPO — tested

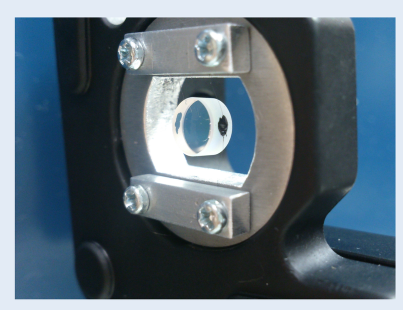
SRMI's transfer function



Suspended compact mirror

Mass — 200 mg
Resonant frequency
longitudinal — 23 Hz
pitch, yaw — 33 Hz
Wire Material — tungsten

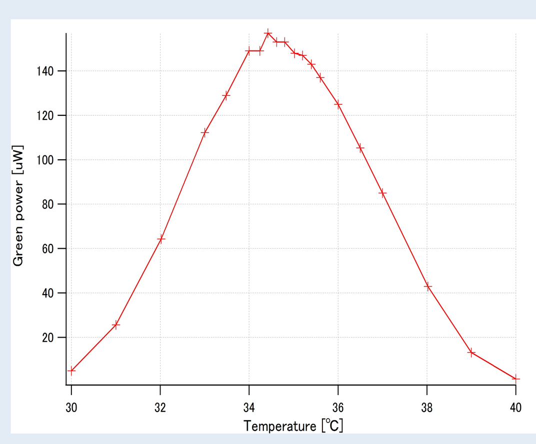




Nonlinear optics

Material — PPKTP
Conversion efficiency (one-pass)

$$E_{NL} = \frac{P_{SHG}}{P_0^{\,2}} \sim 0.005\mathrm{W}^{-1}$$



Temperature dependence

Future work

- Stabilize the control system to see the optical spring.
- Improve the SHG efficiency to generate higher power pump light to realize the signal amplification.
- Combine two experiments and measure the shift of the optical spring resonance by using the signal amplification.

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