Circumvention of radiation-pressure-induced angular instability of a Fabry-Perot cavity

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Abstract

- In this talk, I mainly talk about the radiation-pressure-induced angular instability of the Fabry-Perot cavity and its circumvention.
- We demonstrated the circumvention of the radiation-pressure-induced angular instability using the angular control system.
- The angular instability, in especially pitch mode, would also appear in Speedmeter.
- We propose installing the angular control system which has the same concept as our control system.

Introduction

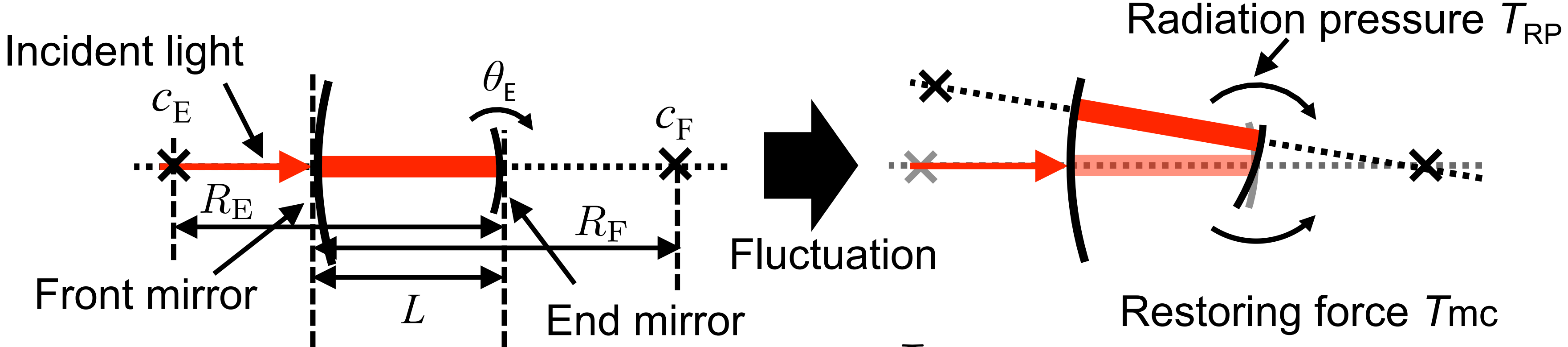
- We have the experiment to **observe radiation pressure noise** and to **demonstrate its evasion using ponderomotive squeezing with homodyne detection**.
- In our experimental setup, to observe radiation pressure noise, the intracavity power is required to be 1 kW.
- However, under such high laser power condition, **radiation pressure caused by resonant light in the suspended cavity could induce the angular instability (Sidles-Sigg instability)** depending on the cavity geometry.

Introduction

- Since we cannot attach any conventional actuator to the 23-mg mirror because of the space constraint, **the 23-mg mirror cannot controlled directly with conventional actuators.**
- For circumventing the radiation-pressure-induced angular instability, we invented **new angular control system that radiation pressure itself is used as an actuator**.

Sidles-Sigg instability

- In a linear cavity, Sidles-Sigg instability could occur if g-factor is positive. (If the cavity has a flat mirror, its g-factor is always positive.)



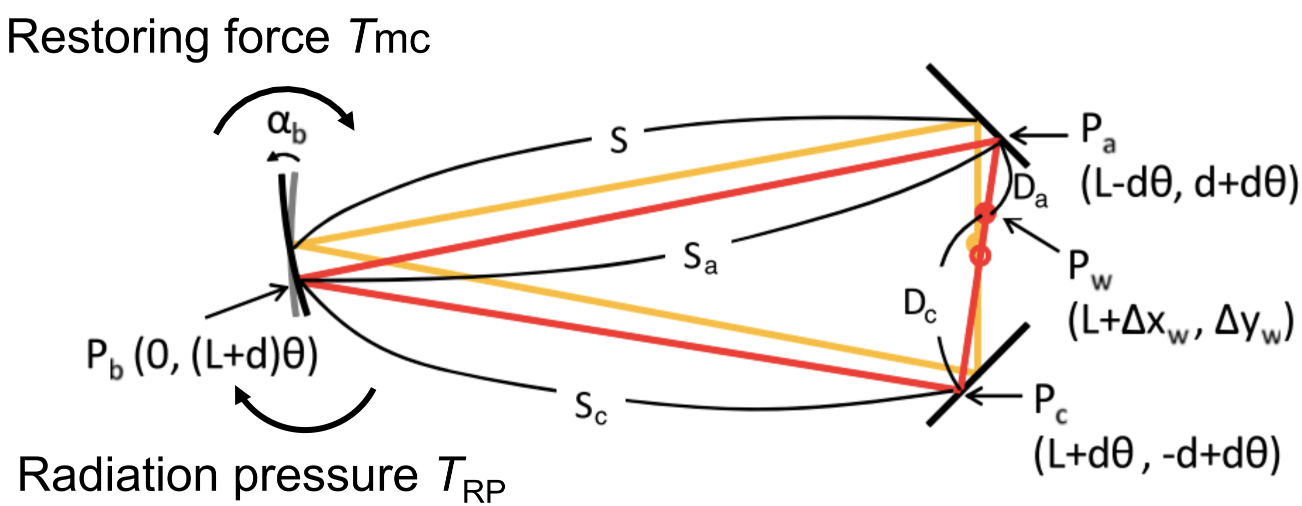
$$T_{\mathrm{RP}} = F_{\mathrm{RP}} \frac{L g_{\mathrm{E}}}{1 - g_{\mathrm{F}} g_{\mathrm{E}}} \theta_{\mathrm{E}}$$

- **Radiation pressure works as an anti-spring.**

(=Rotational resonant frequency is decreased by radiation pressure.)

Sidles-Sigg instability

- In a triangular cavity, the Sidles-Sigg instability is voluntarily circumvented.



F. Kawazoe *et al.*, Journal of Optics, **13**, 055504, 2011

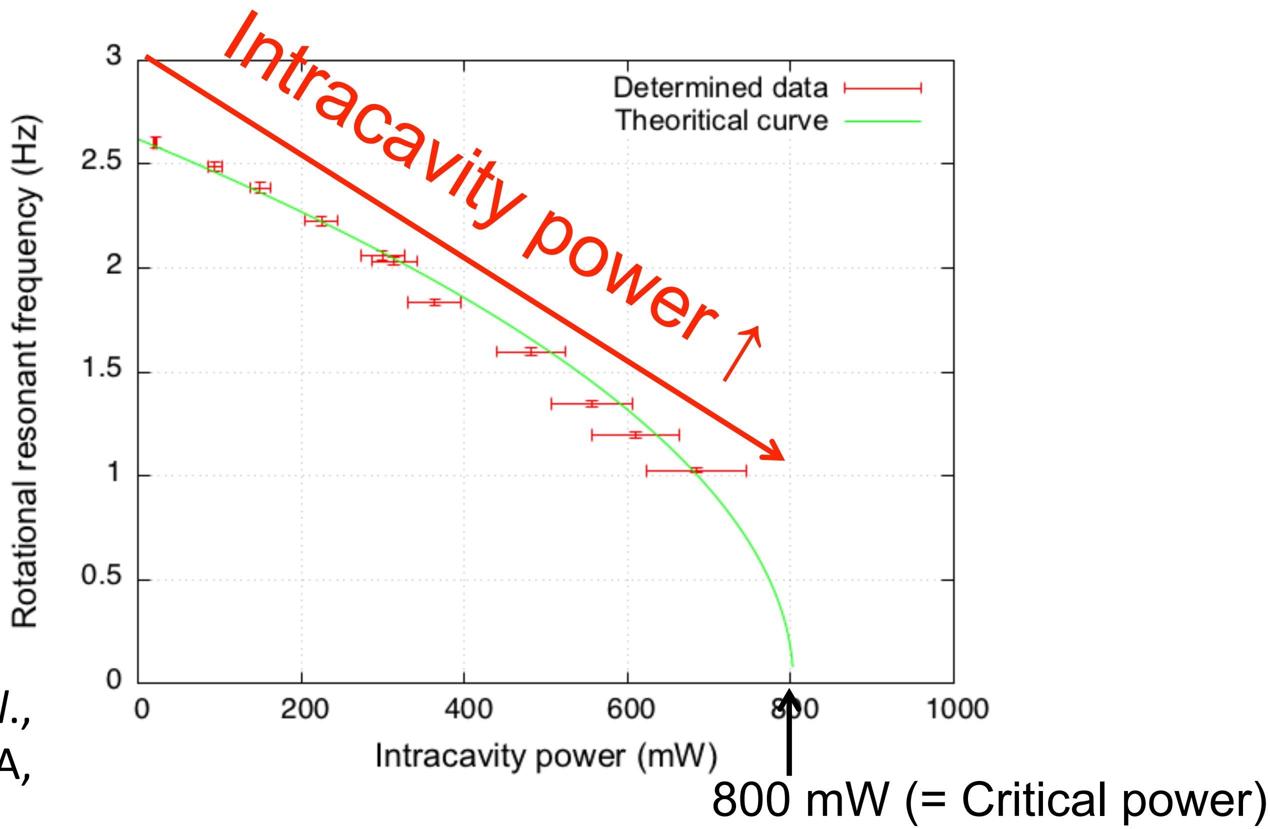
- **<u>Radiation pressure works as a spring.</u>**

Sidles-Sigg instability

- **In our experiment (linear cavity with 23-mg flat mirror)**
  - **In Yaw and Pitch mode, Sidles-Sigg instability could appear**. In especially, yaw-mode instability is serious since the 23-mg mirror is suspended by a single fiber on the top and yaw mode is softer.
- **In Speedmeter (triangular cavity)**
  - Yaw-mode instability wouldn’t occur.
  - However, **pitch-mode instability would occur** since pitch mode behaves as a “linear” cavity.

Anti-spring effect in our experiment

- **The decrease of the 23-mg mirror's rotational resonant frequency was measured.**



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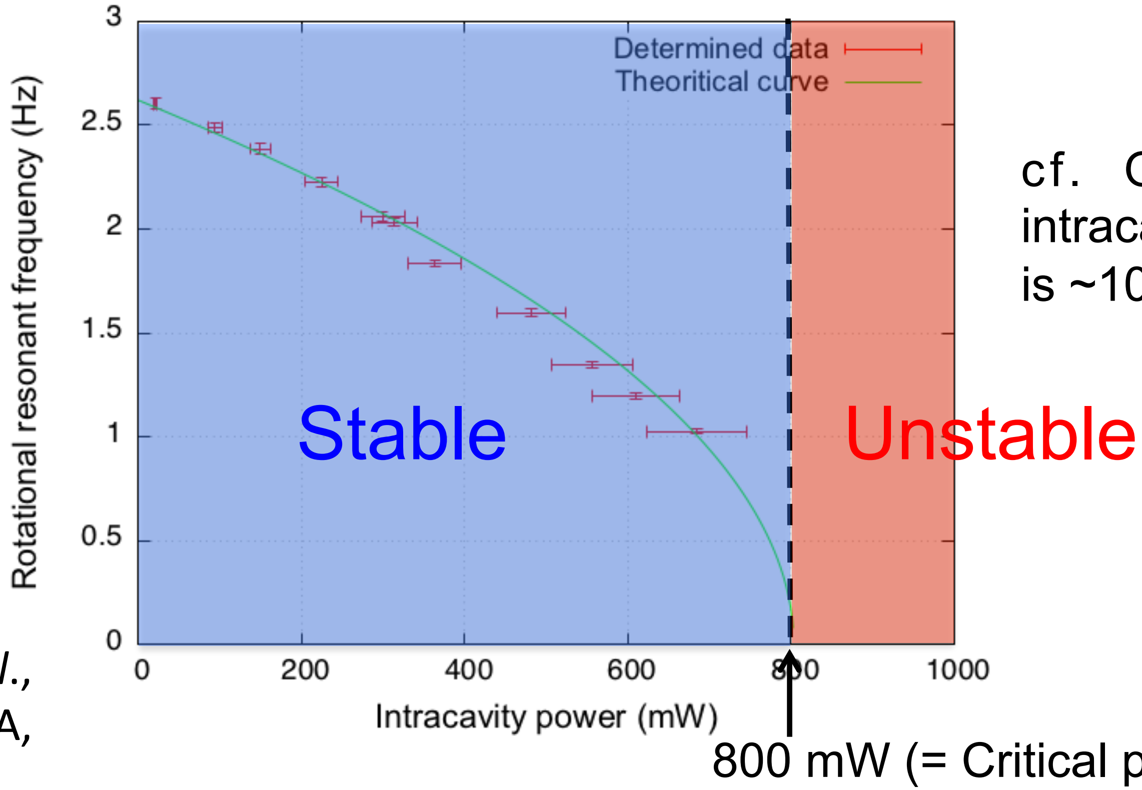
Anti-spring effect in our experiment

- **If intracavity power is lager than the critical power, the cavity should be unstable because of the Sidles-Sigg instability.**



cf. Our target intracavity power is ~10 W – 1 kW.

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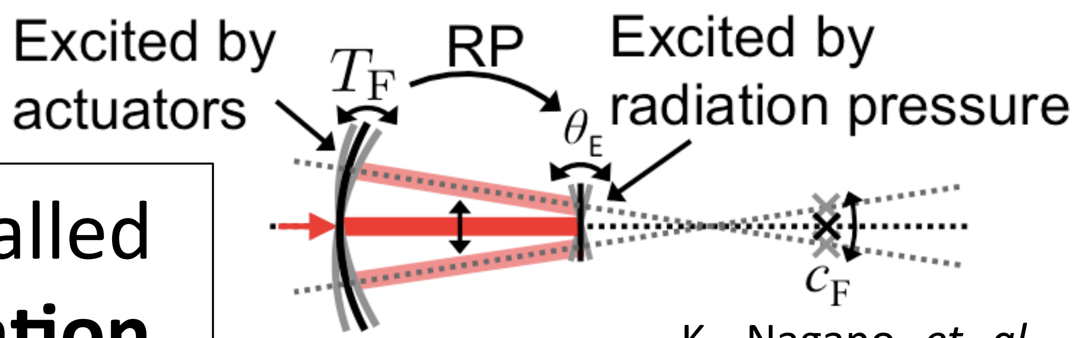
Anti-spring effect in our experiment

- By the way, **how to measure the resonant frequency of the 23-mg mirror, which has no conventional actuator?** In other words, how to excite the yaw-mode of the 23-mg mirror and measure its susceptibility?
- **We excited the 23-mg mirror yaw-mode remotely using radiation pressure itself as an actuator**, i.e. we excited the other 1-inch mirror in the cavity, which has coil-magnet actuators.



This method is called as **remote excitation**.

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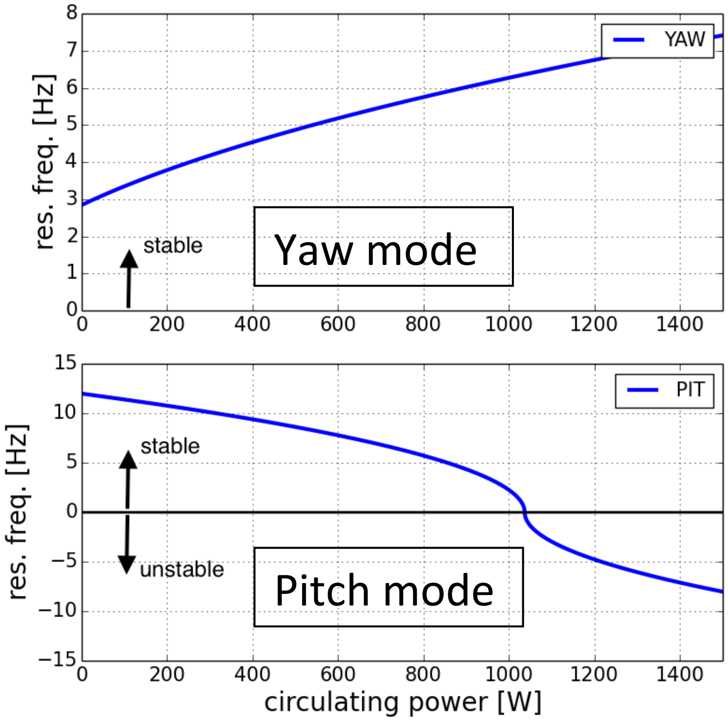
Anti-spring effect in Speedmeter

- The behavior of the rotational (yaw- and pitch-mode) resonant frequency of the 1-g mirror was calculated. (Please note that this is still preliminary.)



Yaw mode looks OK thanks to triangular cavity.

<u>Pitch mode needs to be controlled.</u>

https://arran.physics.gla.ac.uk/wp/speedmeter/2016/06/06/angular-instability-of-arm-triangular-cavities/

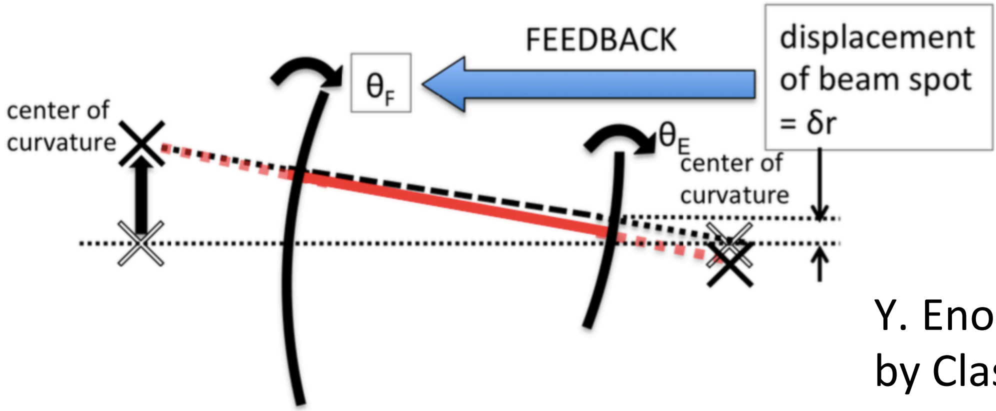
Circumvention of Sidles-Sigg instability

- **To obtain the intracavity power larger than the critical power, the cavity must be controlled angularly.**
- In our experiment, the yaw-mode instability is more serious.
- The 23-mg mirror has no actuator.
- What can we do?
  - The only mirror we can actuate is the 1-inch mirror.
- **Can we circumvent the Sidles-Sigg instability by actuating only the 1-inch mirror?**
  - **Yes!**

Circumvention of Sidles-Sigg instability

<u>Strategy</u>

- Sidles-Sigg instability is generated by the radiation-pressure-induced torque. The torque is produced by the displacement of the beam spot on the 23-mg mirror.
- Therefore **the instability can be circumvented if the beam spot is fixed at the center of the mass of the 23-mg mirror using feedback control .**
- Control scheme is shown as follows:



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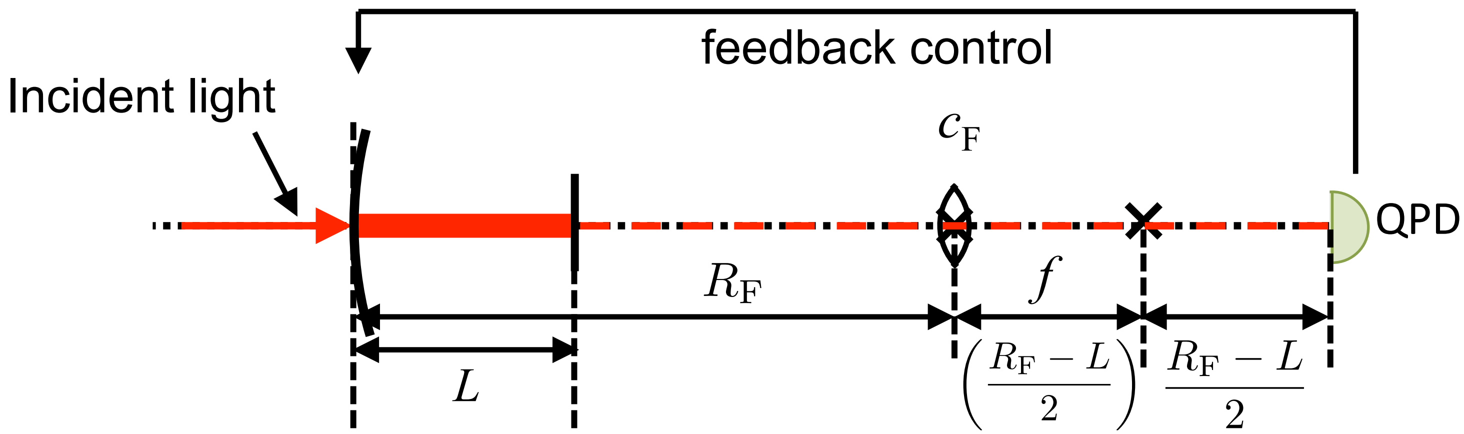
Circumvention of Sidles-Sigg instability

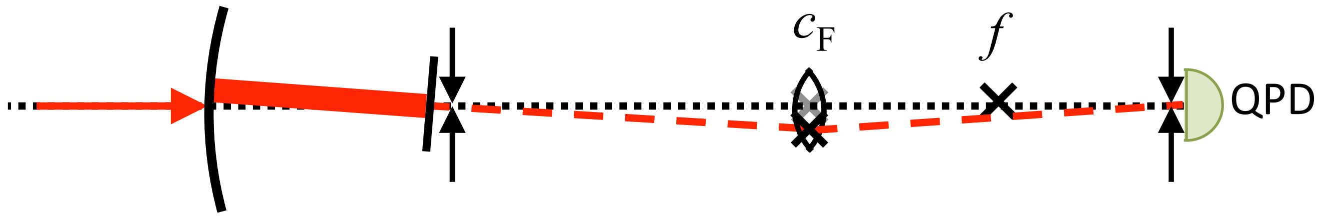
How to measure the displacement of the beam spot on the 23-mg mirror?

- We are measuring the transmitted light position under a certain optical geometry as follows.



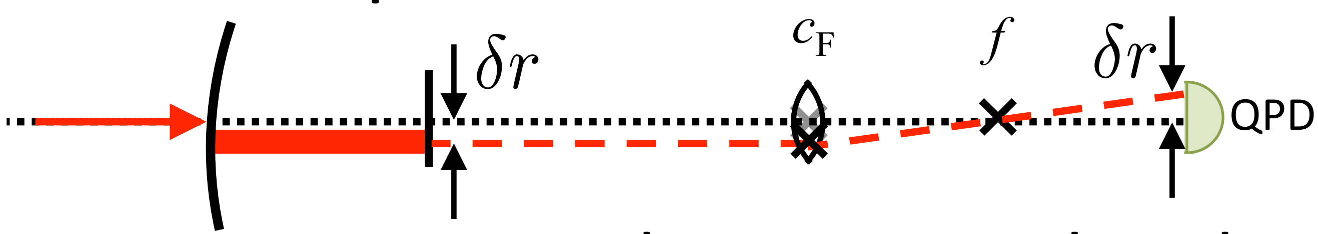
Circumvention of Sidles-Sigg instability

Case 1. Beam spot on the end mirror is at center (tilt)



→ QPD does not output any signal.

Case 2. Beam spot on the end mirror is off.

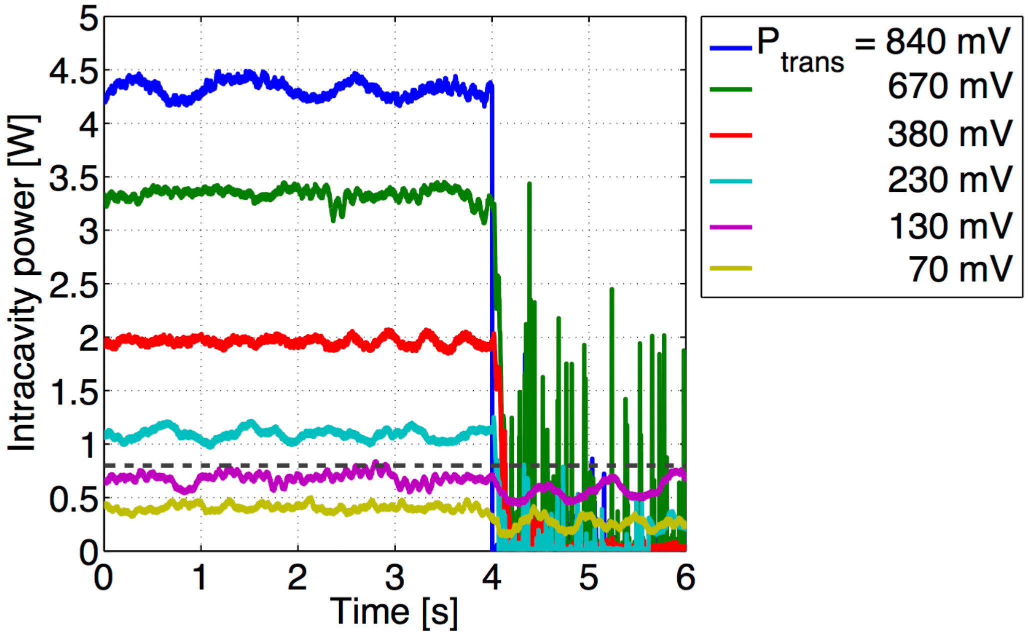


→ QPD outputs a signal proportional to the displacement on the end mirror.

<u>Note that any cavity axis misalignment can be represented by the linear combination of these two tilt and off.</u>

Circumvention of Sidles-Sigg instability

- With the angular control system, the intracavity power can be increased to the power larger than the critical power (0.8 W).
- **The Sidles-Sigg instability is circumvented!**



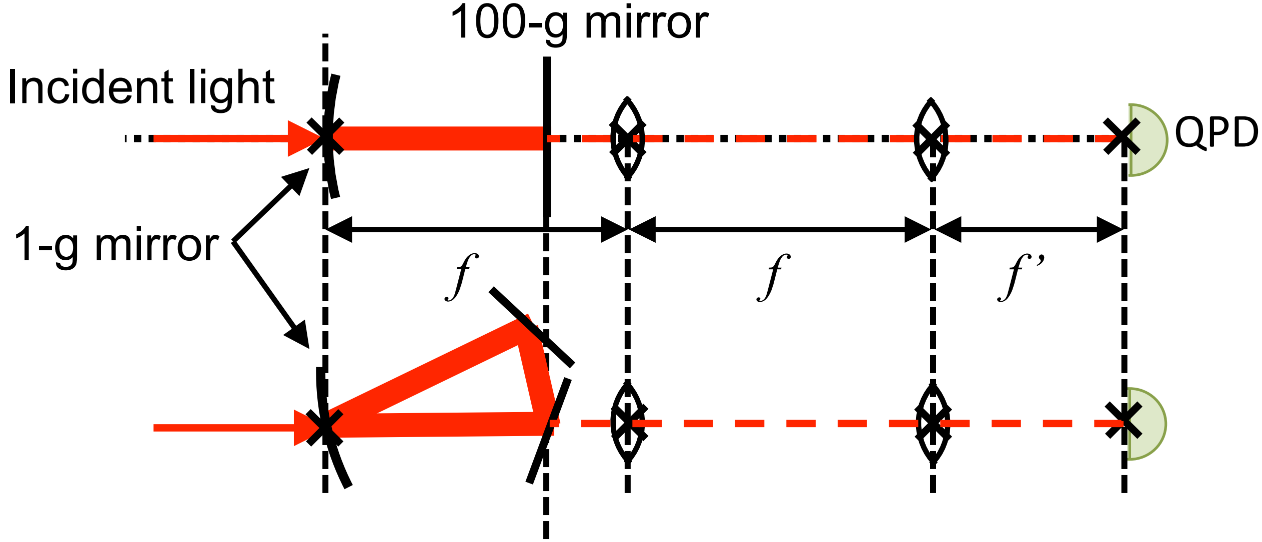
Application for Speedmeter

- As we mentioned before, in Speedmeter, the pitch mode should be controlled.
- The pitch mode control may be achieved with the same method as our experiment.
- In other words, the angular control system that the displacement of the beam spot on the 1-g mirror is fed back to angular motion of the 100-g mirror may be able to be used.

Application for Speedmeter

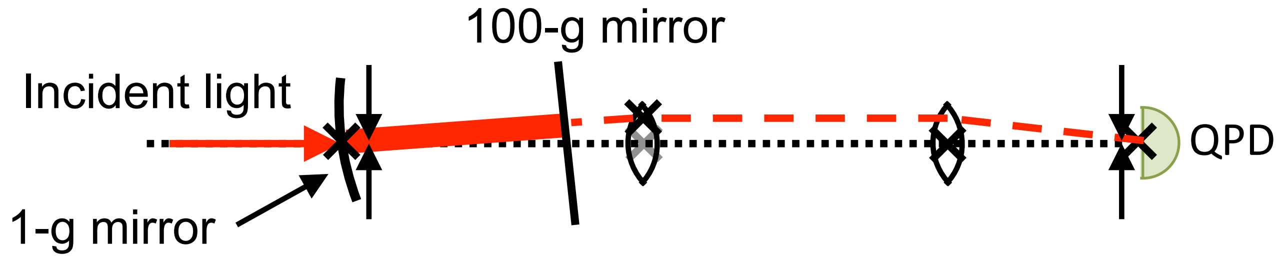
How to measure the displacement of the beam spot on the 1-g mirror?

- The displacement of the pitch mode can be measured with the optical geometry as follows:



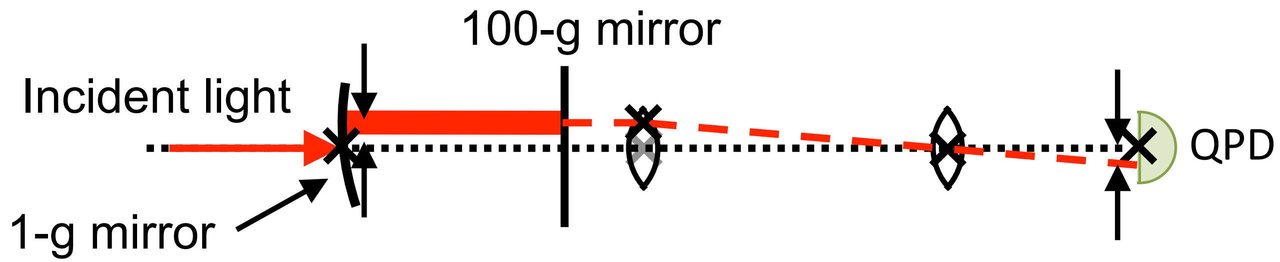
Application for Speedmeter

Case 1. Beam spot on the 1-g mirror is at center (tilt)



→ QPD does not output any signal.

Case 2. Beam spot on the 1-g mirror is off.



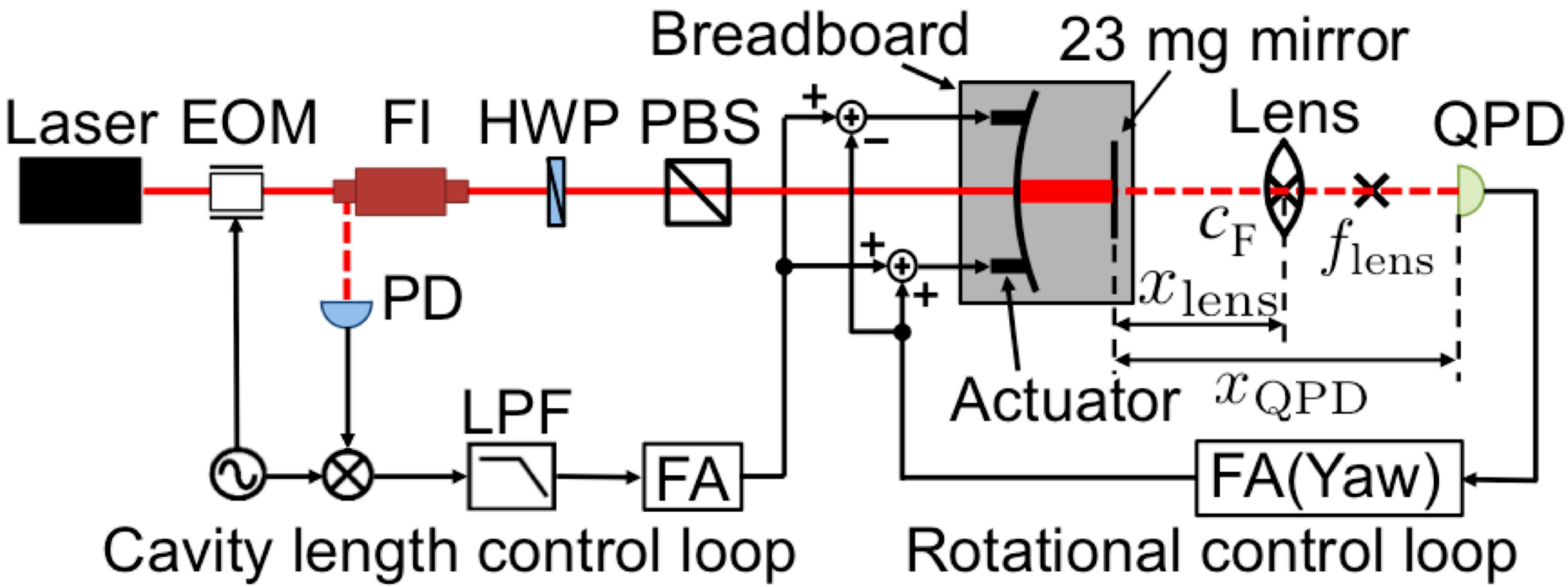
→ QPD outputs a signal proportional to the displacement on the 1-g mirror.

Conclusion

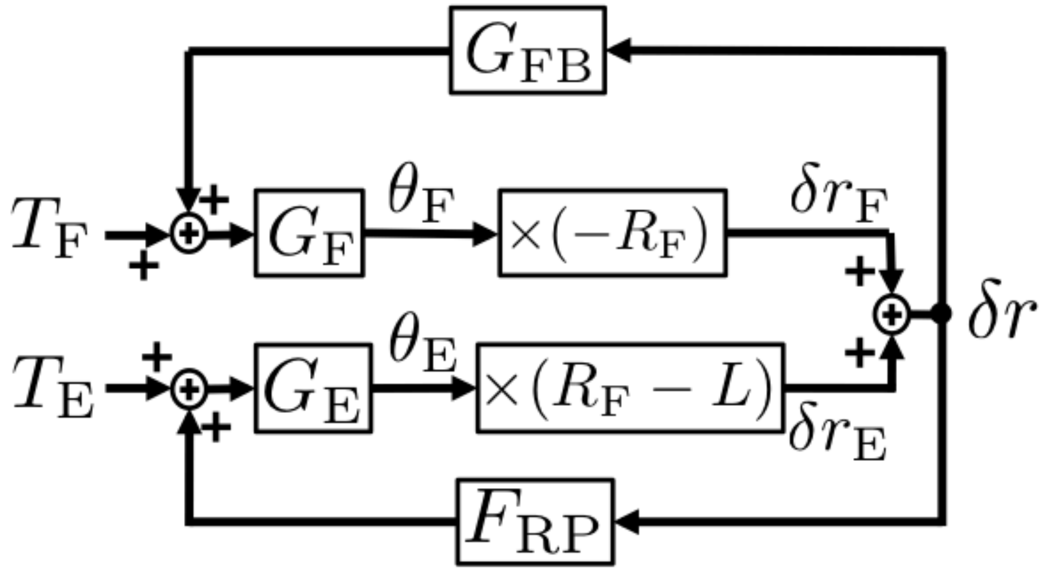
- To obtain the large intracavity power, the Sidles-Sigg instability must be circumvented.
- In our experiment, the yaw-mode and, in Speedmeter, the pitch-mode instability is serious, at first.
- We invented the angular control system to avoid the Sidles-Sigg instability and demonstrated the circumvention of the instability with the angular control system.
- In Speedmeter, to control the pitch-mode instability, the angular control system which has the same concept as ours may be able to be used.

Appendix

Experimental setup

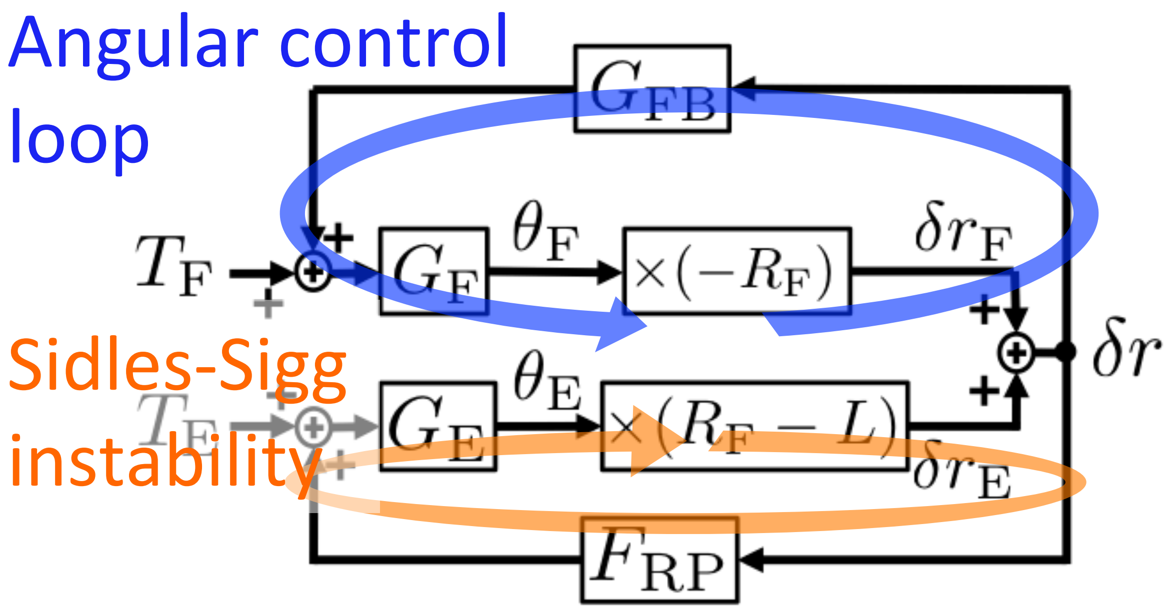


Block diagram of the angular loop



Block diagram of the rotational mode and angular control system of the cavity.

Block diagram of the angular loop



Block diagram of the rotational mode and angular control system of the cavity.

Anti-spring effect reduction

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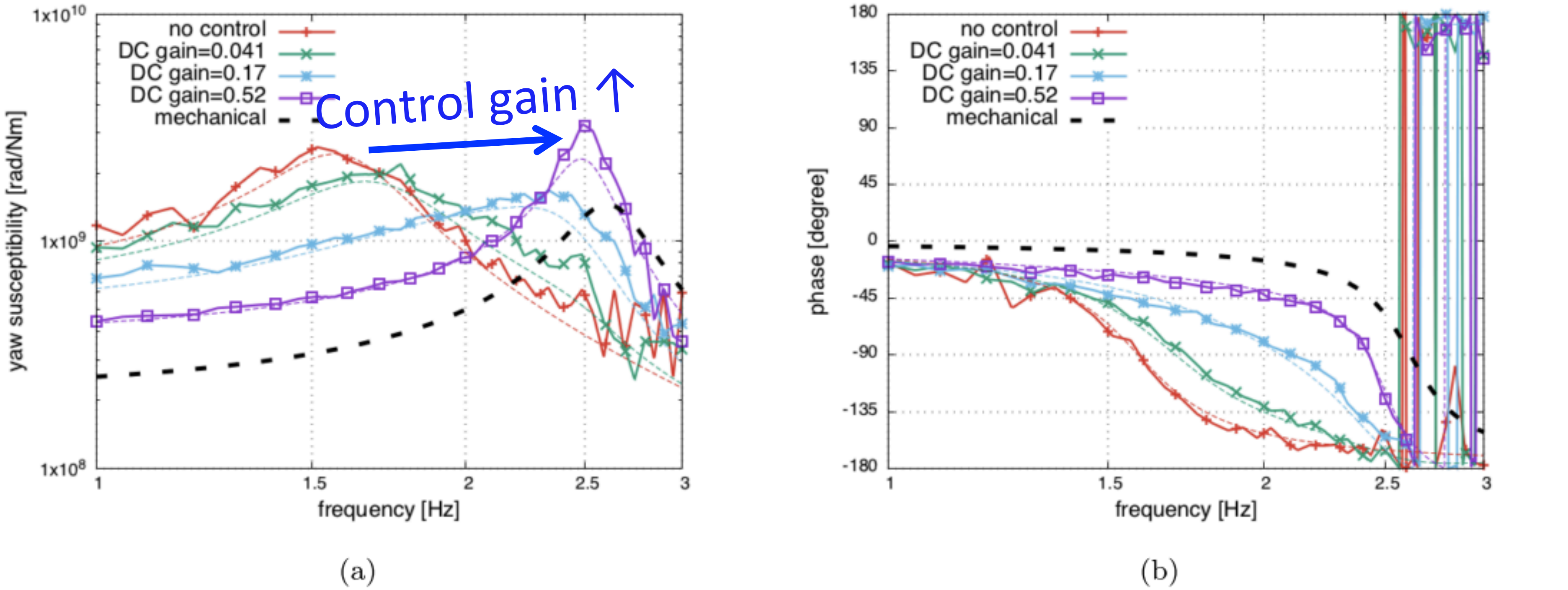

Figure 7. Obtained susceptibilities of the yaw motion of the tiny mirror, $\theta_{\mathrm{E}}/T_{\mathrm{E}}$. Four susceptibilities out of eight are drawn as representative for the same reason as is mentioned in the caption of figure 6. Thick lines with markers correspond to measured data, thin dashed lines correspond to theoretical curves, and a bold dashed line is the mechanical transfer function, G_{E}.

Anti-spring effect reduction

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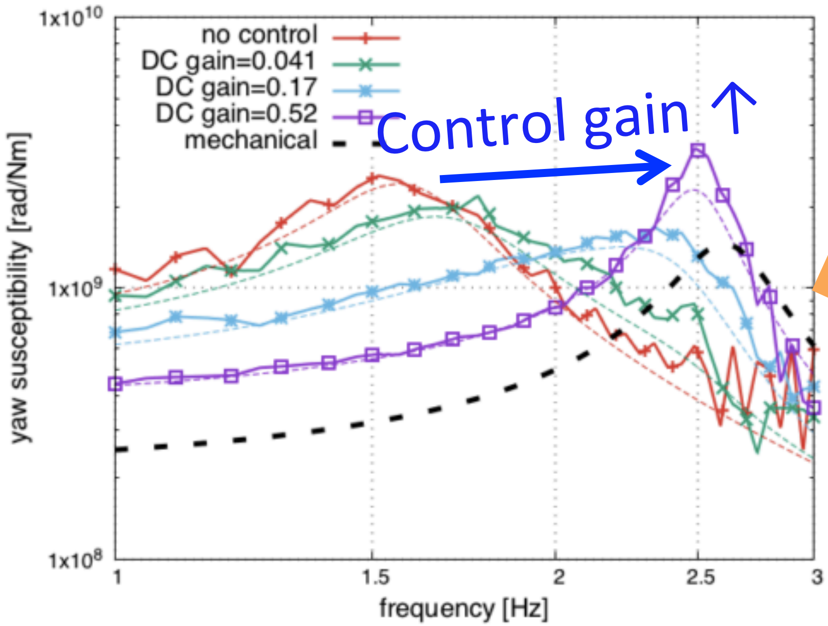

(a)

Figure 7. Obtained susceptibi
Four susceptibilities out of eight
mentioned in the caption of figur
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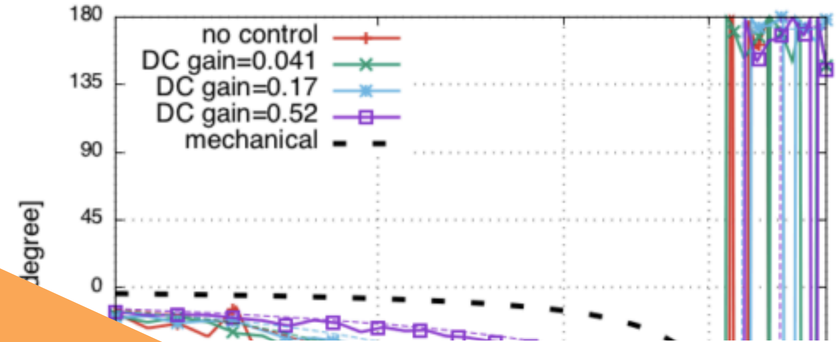
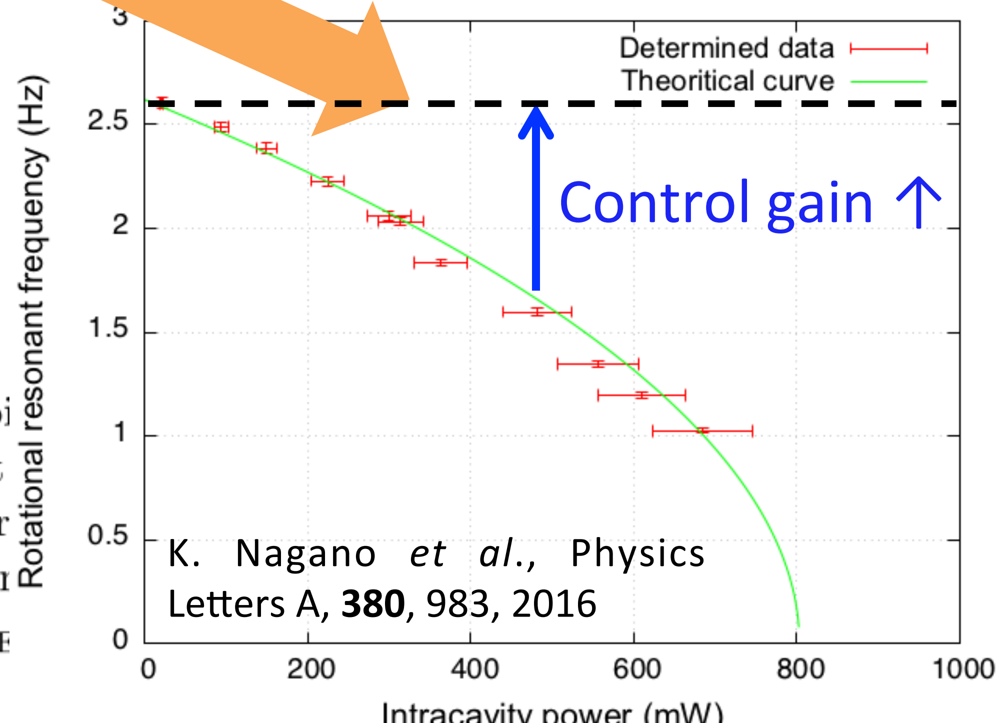
mechanical transfer function, G_{F}





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Nyquist plot of angular control loop