Reduction of quantum noise for gravitational wave detector KAGRA (II)

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Abstract

For observing radiation pressure noise appearing in an optical cavity consisting of suspended mirrors, high lase power is necessary. However, since the radiation pressure applied on the mirrors could cause angular anti-spring effect depending on the optical geometry of the cavity, the high laser power could induce angular instability to the cavity. An angular control system using radiation pressure itself as an actuator, which was previously invented to reduce the anti-spring effect for the lower power case, was applied to the higher power case where the angular instability would be induce. As a result the angular instability was successfully circumvented. It was also demonstrated that the cavity was indeed unstable without this control system.

1. Introduction

- Quantum noise, which consists of shot noise and radiation pressure noise, mainly limits the sensitivity of KAGRA [1].
- **In KAGRA, for reducing radiation pressure noise, the ponderomotive squeezing technique with homodyne detection is going to be used (Fig.1).**

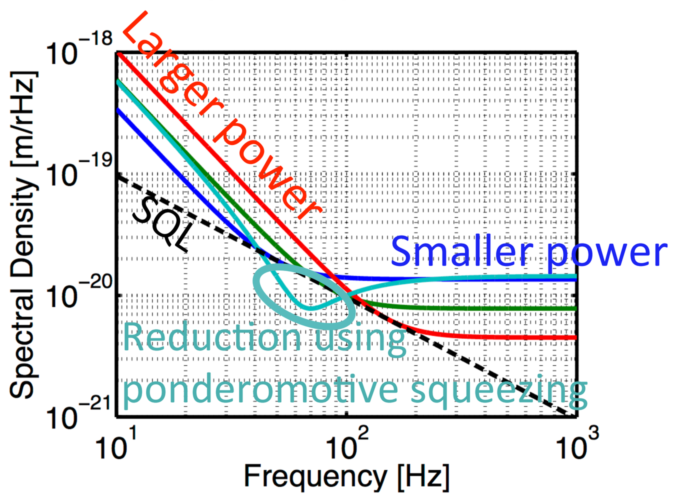

Fig. 1: Noise spectrums of quantum noise at various laser power and noise spectrum reduced by the ponderomotive squeezing technique.

- For demonstrating the ponderomotive squeezing technique, **we have the experiment with the cavity consisting of a suspended 23-mg tiny mirror (Fig. 2), which is used to enhance radiation pressure noise** [2]. Current sensitivity of the cavity is limited by laser frequency noise and the dark noise of a photodetecter.
  (For more information, please also see the Y. Enomoto's poster.)

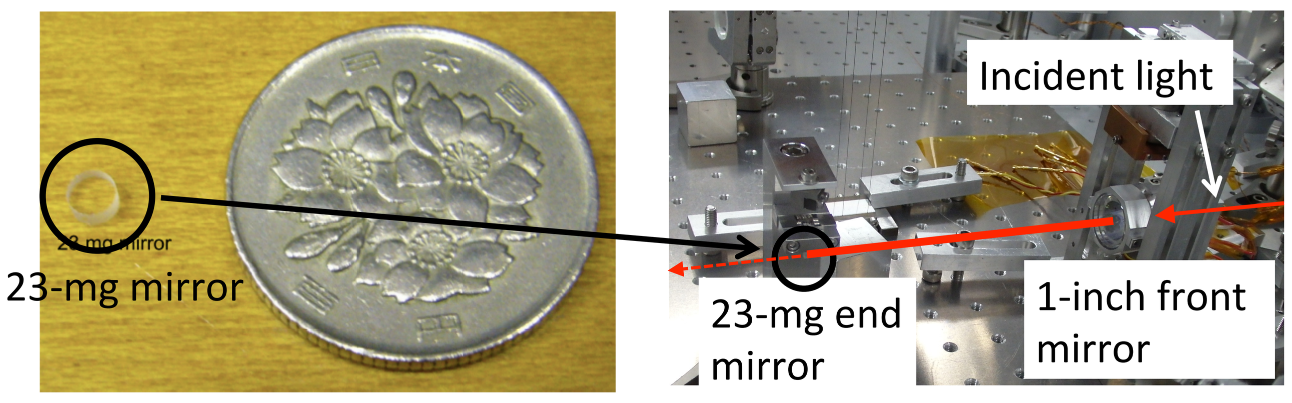

Fig. 2: (Left) Tiny 23-mg end mirror. (Right) Cavity consisting of the 23-mg mirror.

- For observing radiation pressure noise, high laser power is necessary. However, since radiation pressure (RP) applied on the mirror could cause angular anti-spring effect depending on the cavity geometry [3,4], **the high laser power could induce the angular instability to the cavity (Fig. 3)**. This radiation pressure induced angular instability is called as Sidles-Sigg instability.

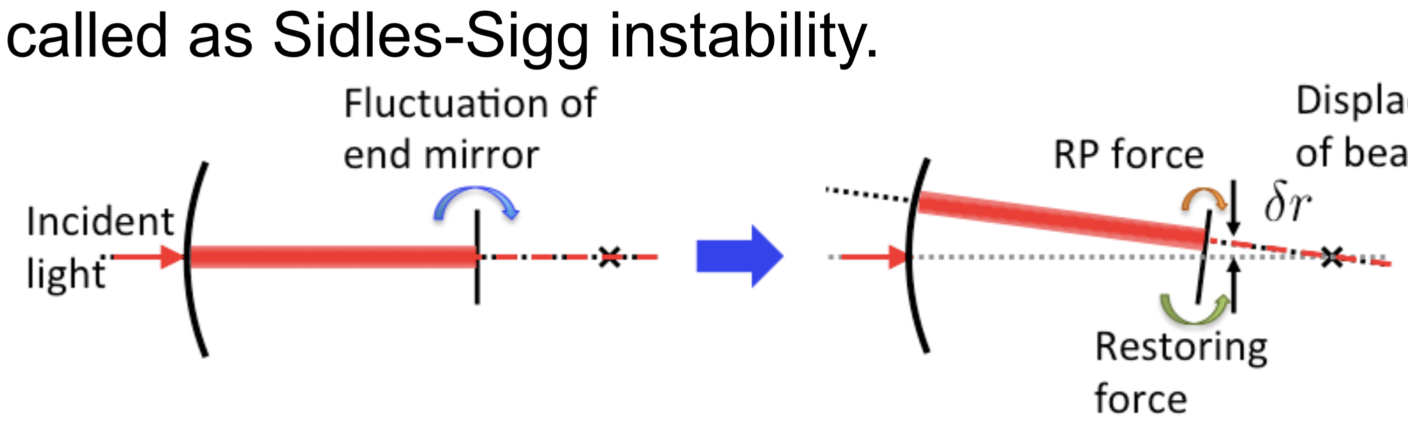

Fig. 3: Schematic of the Sidles-Sigg instability.

- **For reducing the optical angular anti-spring effect of the cavity, an angular control system using radiation pressure itself as an actuator was invented** [5,6]. In this control system, the displacement of the beam spot on the tiny mirror is fed back to the angular motion of the normal size front mirror (Fig. 4).
  → **We have to demonstrated the circumvention of the radiation-pressure-induced angular instability using this control system under high laser power condition.**

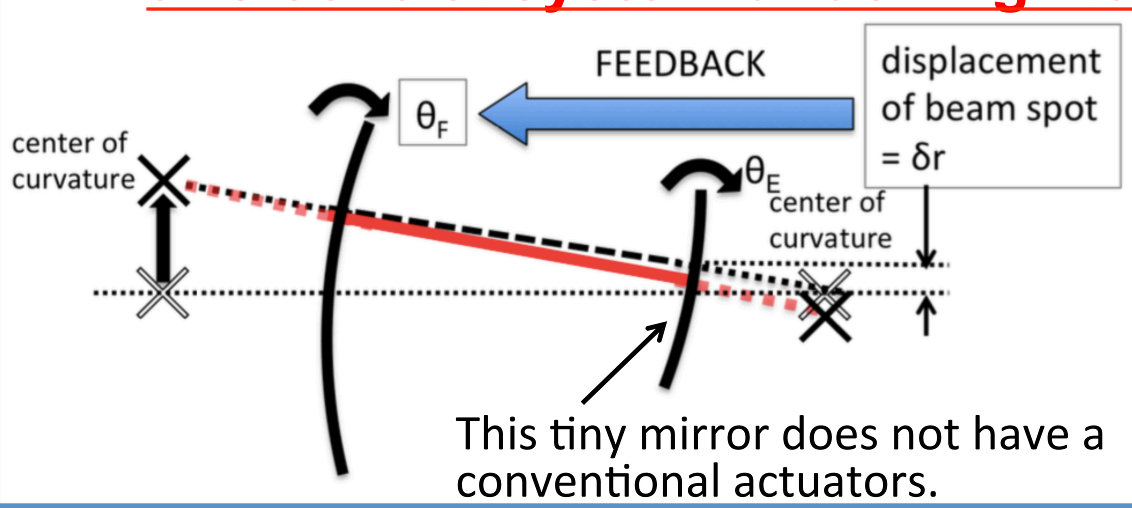

Fig. 4: Schematic of the angular control system. Using this control system, the beam spot on the end mirror is kept at center. Hence, the optical anti-spring effect is reduced [6].

2. Method

- There are two ways to demonstrate the circumvention of the radiation-pressure-induced angular instability:

1. Observing time series data of the intracavity power
   - From this data, we can determine the magnitude of the optical anti-spring effect. When the optical anti-spring effect is larger than the mechanical spring effect, the cavity would be unstable without the angular control system.
2. Open loop gain analysis
   - The block diagram of the rotational mode of the cavity is shown as Fig. 5. The lower loop in Fig. 5 (defined as G_{EML}) induces the angular instability. The upper loop in Fig. 5 is the applied angular control system as shown in Fig. 4 and reduces the optical anti-spring effect. From the measurement of G_{EML}, we can know whether the cavity is unstable without the angular control system with the loop gain analysis, such as Bode plot and Nyquist plot.

- **From these two data, the circumvention of the radiation-pressure-induced angular instability using the angular control system can be demonstrated.**

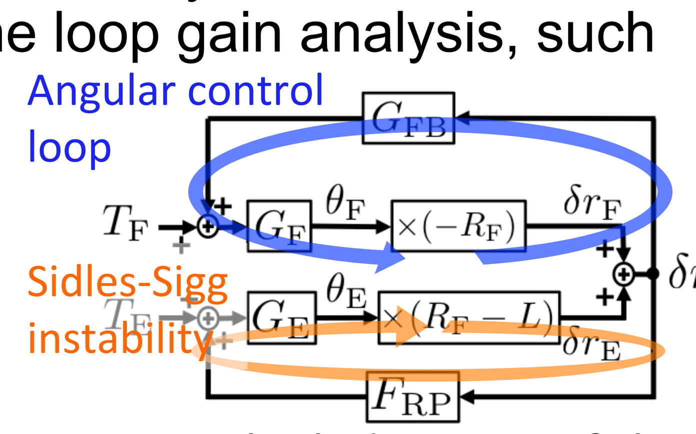

Fig. 5: Block diagram of the rotational mode and angular control system of the cavity.

3. Result and discussion

1. Time series data of the intracavity power
   - With the angular control system, **the cavity could be operated in the condition where the optical anti-spring effect is larger than the mechanical spring effect without the angular control system.**

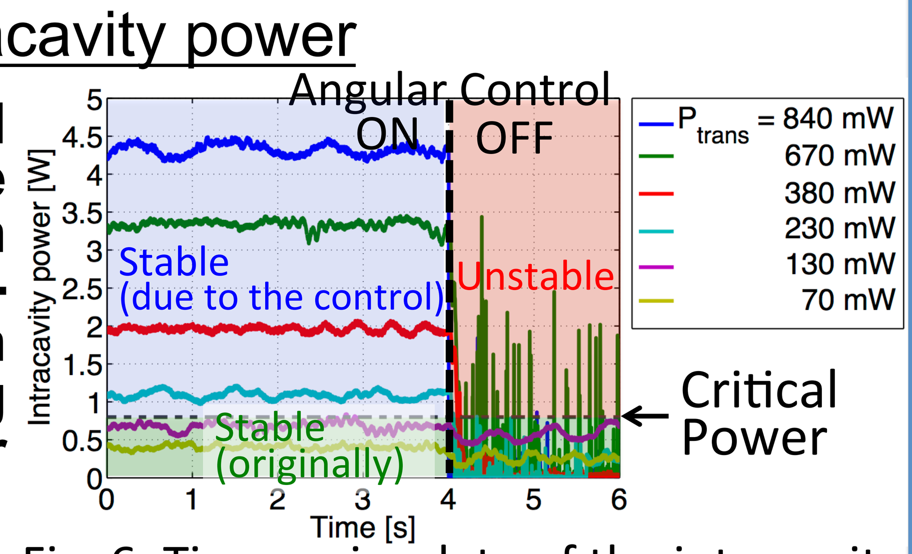

Fig. 6: Time series data of the intracavity power at several laser powers.

2. Open loop gain analysis
   - Under high laser power condition, **the cavity was operated stably with the angular control although the cavity would be unstable without the angular control.** (Fig. 7).

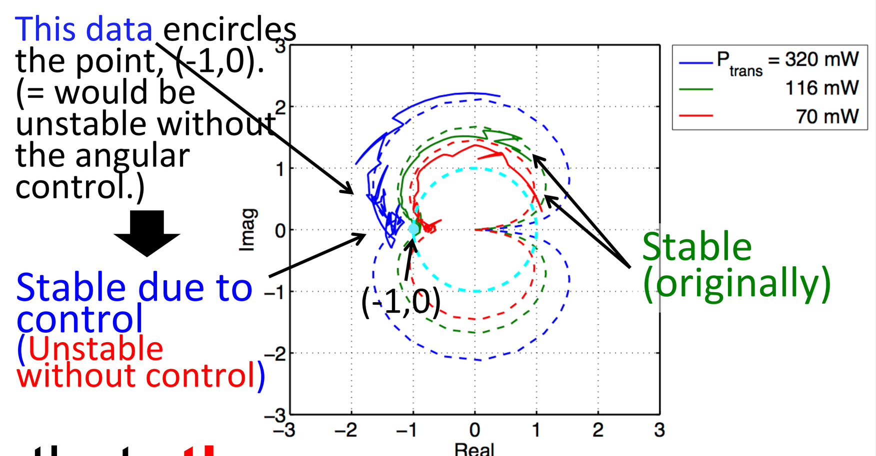

Fig. 7: Nyquist plots of measured (determined) G_{EML} at three laser powers. Here, the moving radius is defined as $\log_{10}(|G_{EML}|)+1$.

- These two results indicate that **the cavity is operated stably with the angular control under high laser power condition in spite of Sidles-Sigg instability**.
- Under this condition, it is also confirmed that **the cavity is indeed unstable without the angular control**.

4. Conclusion

- Using the angular control system, **the radiation-pressure-induced angular instability was circumvented**.
  → **This result leads to the operation of the cavity consisting of the suspended 23-mg mirror under high laser power condition for enhancing and observing radiation pressure noise in wide frequency range.**

Reference

[1] K. Somiya, *Class. Quantum Grav.*, **29**, 124007, 2012 [2] S. Sakata, Ochanomizu Univ., Ph.D. thesis, 2008 [3] J. Sidles, and D. Sigg, *Phys. Lett. A*, **354**, 167, 2006 [4] K. Nagano et al., *Phys. Lett. A*, **380**, 983, 2016 [5] M. Nakano, Univ. Tokyo, Master thesis, 2014 [6] Y. Enomoto et al., Submitted to Class. Quantum Grav.