## 5 Software approach against RSE of KAGRA

KAGRA will use RSE as the interferometric configuration for quantum noise reduction. In this configuration, the arm cavity finesse could be higher, while the power recycling gain is lower. Therefore the thermal noise on beam splitter could be reduced.

In KAGRA, there are some options for locking methods by hardware methods, i.e. green laser, digital interferometer, suspension point interferometer. One of reasons of its difficulty to acquire the lock is high finesse of cavities. And there is not one established method. As one backup solution, suggesting that a software method, which means by just signal from interferometer, cavity could be acquired lock. Having that software method, in case that Green Laser failed, this solution could be applied without any installation of hardware. Also, even supposing that Green Laser succeeded, if Guided Lock were verified that it is more effective than Green Laser, this new software method could be default plan for KAGRA.

RSE lock acquisition step is recommended as follow.

1. Central part locking
2. Central part locking hold
3. Fabry Perot cavity locking

As the first, verify the effectiveness of a new Guided Lock method for locking the Fabry Perot cavity, and second the central part lock holding by constraint end test mass. These simulations are executed by End to End (e2e) simulator.

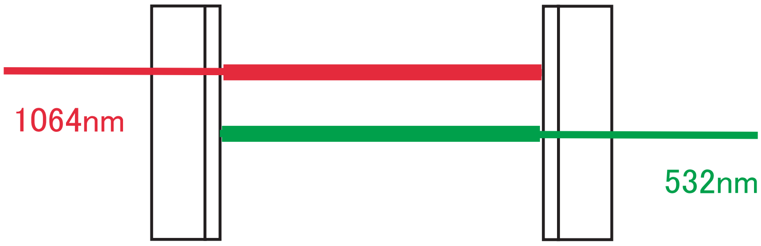


Figure 22: Green laser concept

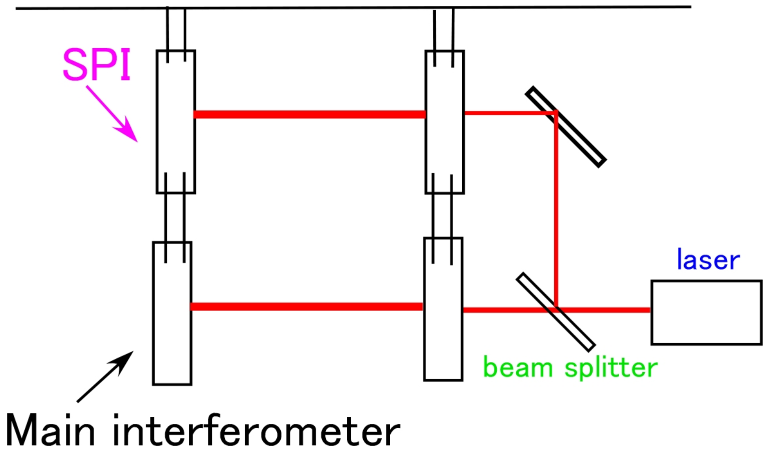


Figure 23: SPI configulation

### 5.1 Options for lock acquisition

There are some methods to acquire the lock of full length.

- Green laser
  - Arm cavities are made locked by this shorter wave length, consequently, shifted to main laser wave length. The reflectivity of green laser is estimated less than the 1064nm laser. Therefore the finesse for green laser is less and to lock the cavity with green laser is much easier than with 1064nm laser.
  - aLIGO or KAGRA
- Suspension point interferometer (SPI)

  - SPI is cavity system combined at the upper level of main cavity. SPI reduce the amplitude of the mirror root mean square (RMS) by the rigid bar upon the main cavity.

- Pound Drever Hall method (PDH)
  - PDH is the feed back control with pre-modulated and demodulated signals. The error signal could be earned to feed back to end mirror to control.

- Guided Lock
  - This is the optimized deceleration for acquiring lock.

- Sideband error signal
  - Measure the mirror velocity by differential of the error signal. Then

  - Predict the motion of mirror by measurement the mirror velocity using error signal of sideband.

- $TEM_{NM}$ to misaligned cavity length

- Using large power only when Lock acquisition is executed

- Choose the mid of I and Q phase for demodulation

Those ideas require instruments and times for installation. Therefore we now try to seek how to lock the full length without any hardware. There should be some solutions for lock acquisition of RSE using 9 signals from RSE. In this thesis, the idea for RSE lock acquisition is suggested.

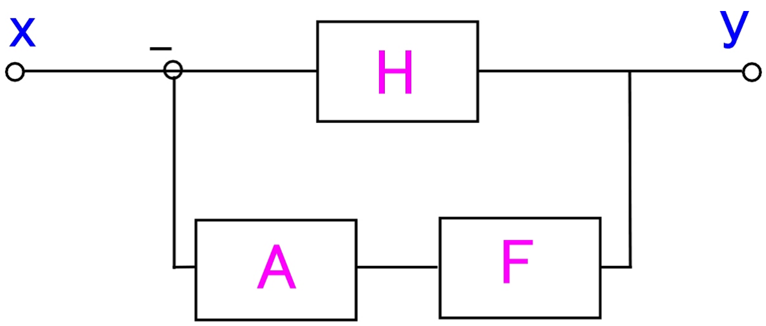


Figure 24: Control scheme

### 5.2 Control theory

Here supposed that input x, output y, sensor H, filter F and actuator A. this loop is closed with feed back control. In this loop, output y is written by input x, H, F, A.

$$y = \frac{H}{1 + AFH} x$$

- Sensor
  - Fabry Perot cavity: Sensing the light power by cavities displacement.
- Filter
  - Low pass filter: Cutting the high frequency power from mixer.
- Actuator
  - Coil magnet actuator: Using the magnetic force by electric current.

Unity gain frequency (UGF) is the one indicate of the servo stability.

### 5.3 Pound Drever Hall method

Pound-Drever-Hall technique is one of the length control method. To obtain the cavity length, inject the modulated field to the system. And demodulate the reflected power from cavity by some phase

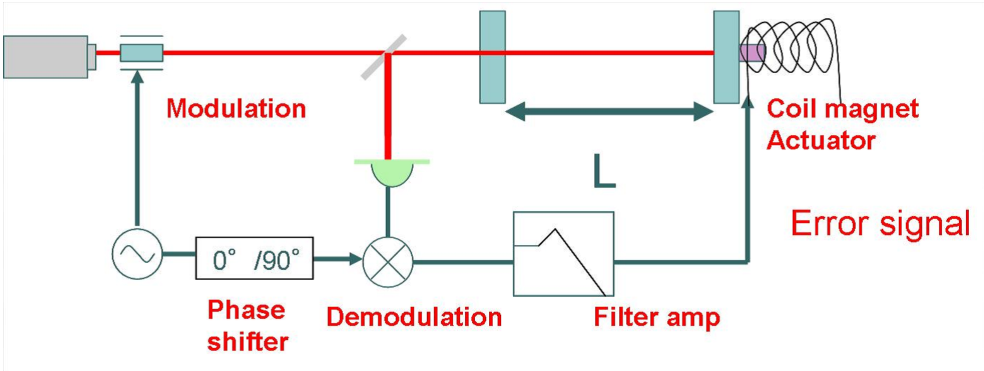


Figure 25: Pound Drever Hall scheme

(0°/90°) after the photo detector. This demodulated power has dc and $2\omega_m$ components. Then with the low pass filter the dc proportional to displacement signal could be obtained. Feeding back this signal to the cavity, the system could be stabilized to the resonating cavity.

**Modulation** Modulation is divided into amplitude modulation (AM) and phase modulation (PM). Supposing the modulation index m, frequency $\omega_m$ and original beam $E_0 = A_0 e^{i\omega_0 t}$, the amplitude modulated beam$E'$ is represented as

$$\begin{aligned} E' &= A_0[1 + m\cos\omega_m t]e^{i\omega t}] \\ &= A_0[1 + \frac{m}{2}\left(e^{i\omega_m t} + e^{-i\omega_m t}\right)]e^{i\omega t} \\ &= A_0 e^{i\omega t} + A_0\frac{m}{2}e^{i(\omega+\omega_m)t} + A_0\frac{m}{2}e^{i(\omega t - i\omega_m)t} \end{aligned} \tag{46}$$

The first term is carrier, the second is upper sideband and third is lower sideband. On the other hand, the phase modulated beam $E''$ is as follow under the same conventions.

$$\begin{aligned} E'' &= A_0 e^{im\cos\omega_m t}e^{i\omega t}] \\ &= A_0[1 + \frac{m}{2}\left(e^{i\omega_m t} + e^{-i\omega_m t}\right)]e^{i\omega t} \\ &= A_0 e^{i\omega t}\cos m\cos\omega_m t + i\sin m\cos\omega_m t \\ |m| \gg 1 &= A_0 e^{i\omega t} + A_0 e^{i\omega t}\frac{im}{2}(e^{i\omega_m t} + e^{-i\omega_m t}) \end{aligned}$$

$$= \quad A_0 e^{i\omega t} + iA_0 \frac{m}{2} e^{i(\omega+\omega_m)t} + iA_0 \frac{m}{2} e^{i(\omega-i\omega_m)t} \tag{47}$$

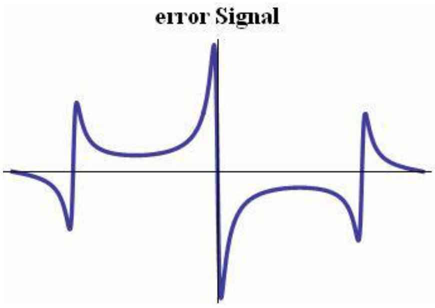


Figure 26: Error Signal

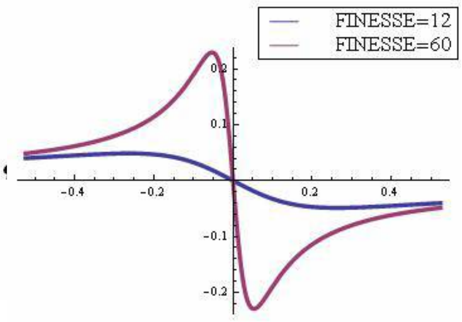


Figure 27: Comparison of linear range

**Error Signal** Assuming that $\delta$ is cavity displacement, $E_{car}$ is field of carrier, $E_{SB}$ is that of sideband. The error signal what is the displacement from right resonant position, is calculated.

$$\text{error Signal} = Im[E_{SB}E^*_{car}] = A\delta$$

This signal has the linear range, which depends on the cavity finesse. The higher finesse makes the range narrower.

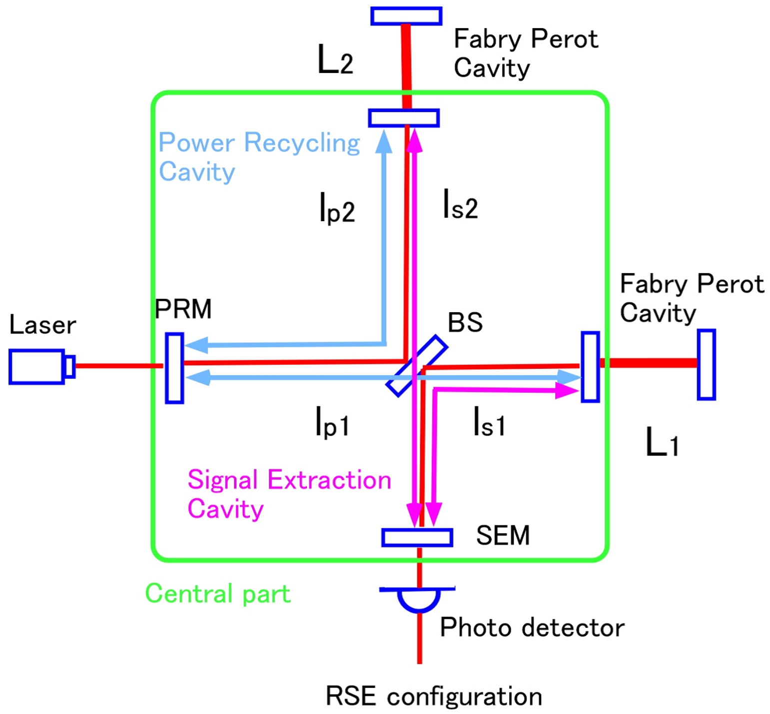


Figure 28: RSE configuration

### 5.4 Software method for RSE lock acquisition

RSE is the advanced configuration. RSE has another mirror at detection port of Power Recycled Michelson Interferometer, which make it possible to enhance the gravitational wave signal. Therefore RSE has 5 degrees of freedom to control. $L_+ = \frac{L_1+L_2}{2}$and$L_- = \frac{L_1-L_2}{2}$ are the common and differential motion of 2 arms. $l_+ = \frac{l_{p1}+l_{p2}}{2}$and$l_- = \frac{l_{p1}-l_{p2}}{2}$ are the common and differential motion of central Michelson. $l_s = \frac{l_{s1}+l_{s2}}{2}$ is the SEM motion. To control those lengths, two modulation and demodulation is applied. At Reflection port(REFL), PRM Pick port(PO) and SEM port(AS), DC signal and demodulated by I phase and Q phase , therefore 9 signals are obtained. Using optimized signals, there is ought to be one software solution to locking full length of RSE.