Optical design and suspension system of the KAGRA output mode-cleaner

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Abstract. KAGRA is a Japanese large scale, underground, cryogenic gravitational telescope which is under construction in the Kamioka mine. For using cryogenic test masses, the sensitivity of KAGRA is limited mainly by quantum noise. In order to reduce quantum noise, KAGRA employs an output mode-cleaner (OMC) at the output port that filters out junk light but allows the gravitational wave signal to go through. The requirement of the KAGRA OMC is even more challenging than other telescopes in the world since KAGRA plans to tune the signal readout phase so that the signal-to-noise ratio for our primary target source can be maximized. A proper selection of optical parameters and anti-vibration devices is required for the robust operation of the OMC. In this proceeding, we show our final results of modal-model simulations, in which we downselected the cavity length, the round-trip Gouy phase shift, the finesse, and the seismic isolation ratio for the suspended optics.

1. Introduction

Gravitational waves are ripples of space-time, first predicted by Albert Einstein nearly 100 years ago [1]. On September 14, 2015, two LIGO observatories succeeded in the first direct detection of gravitational waves and the first observation of a binary black hole merger [2]. At the dawn of the gravitational wave astronomy is approaching, it is essential for the gravitational wave detectors to collaborate together.

KAGRA is an interferometric gravitational telescope which is under construction in the Kamioka mine, Japan [3]. The interferometer has an 3-km Fabry-Perot cavity in each arm, a power-recycling cavity in the symmetric port, and a signal-recycling cavity in the anti-symmetric (AS) port (see Fig. 1, left). The two unique features of KAGRA are (i) the entire interferometer is built underground for less seismic vibration and (ii) the sapphire test masses are cooled down to a cryogenic temperature. The gravitational wave signal is obtained with a DC readout scheme [4], in which a fraction of the carrier light leaking to the AS port is used as a reference field to beat with the gravitational wave signals. To maximize the observation range to our primary target source: binary neutron stars, the signal-recycling cavity is detuned by 3.5 deg and the DC readout phase is tuned to 132 deg. The observation range is then 153 Mpc. In order to tune the readout phase, the reference field power may need to be as small as 1 mW, depending on the imbalance of the two arm cavities. Since the OMC needs to filter out and suppress other light coming out to the AS port with such a small amount of reference light, the requirement to the KAGRA OMC is even more challenging than the OMCs in other telescopes.
2. Output mode-cleaner

2.1. Optical requirement

The OMC filters out radio-frequency (RF) control sidebands and spatial higher order modes of the carrier light as the carrier light and the gravitational wave signal transmits through it. In order for the sensitivity deterioration in the OMC to be within 5%, a possible breakdown of an acceptable degradation is as follows: the signal loss is to be 2% or less, the residual spatial higher order modes are to be $10^{-6}$ W or less, and the residual RF sidebands are to be $20\mu$W or less. The optical parameters of the OMC determined from results of FINESSE [5] simulations are as follows: (i) round-trip cavity length is 1.5 m, (ii) Gouy phase shift is 55.4 deg, (iii) finesse is 780, and (iv) reference field light is 1 mW [6].

2.2. Suspension requirement

Even though all the OMC optics are on a single breadboard, seismic vibration of the OMC system can cause several problems. (i) The signal transmission can be reduced due to optical mode mismatching. (ii) Noise can increase due to modulation to the reference light field. We simulated the degradation of the sensitivity with tilt and mis-centering vibrations of the OMC using FINESSE with artificial mirror maps and calculated the vibration isolation requirement (see Fig. 2, right). We found that the requirement in the horizontal direction is more severe than the vertical direction: the required isolation ratio is 1/100 at 20 Hz. Concerning the vertical-horizontal coupling, we decided to apply the same requirement as the horizontal direction also in the vertical direction. As a result, the OMC should be suspended by three single-stage pendula, each of which supported by a blade spring. (iii) Scattered light may be re-injected from the OMC optics to the main interferometer. Since the solid angle of the KAGRA OMC is $1e^{-6}$ sr and the bidirectional reflectance distribution function is 0.1, the backscattered light of the OMC is 0.1 ppm, which is small enough to not disturb the sensitivity of the interferometer. (iv) The signal transmission can be reduced due to an OMC cavity length change. Deformation of the breadboard at its mechanical resonances may change the OMC optical length. We calculated the resonant frequencies using a Finite Element Method (FEM) simulation and determined the silica board size to be $200 \times 500 \times 50$ mm, which weighs 11 kg; the lowest mechanical mode is then 1145 Hz.
3. Suspension system for the KAGRA OMC

We adapt three blade springs made of MAS-1 (Yield stress: 1.9 GPa) for the OMC vertical seismic isolation. Since the OMC breadboard is not rotationally symmetric, it is essential to design the blade spring to reduce the vertical-horizontal coupling at the working point so that a vertical bounce will not cause a horizontal motion.

The blade spring for the KAGRA OMC is a flat cantilever without load, which is to be curved with a load in a proper radius of curvature, is used to eliminate the vertical-horizontal coupling [7] (see Fig. 3, left). The force applied to the bent blade is expressed by the following formula:

$$\sigma = \frac{Et}{2R^2},$$  \hspace{1cm} (1)

where $\sigma$ is the working stress, $E$ is Young’s modulus, $t$ is the thickness of the blade, and $R$ is the radius of the bent blade spring. The width of the curved blade spring needs to be precisely described by the following equation:

$$w(x) = \frac{6mgR}{\sigma t^2} \sin \left( \frac{x}{R} \right),$$  \hspace{1cm} (2)

where $m$ is the mass of the load and $g$ is the gravitational acceleration. We define the top of the blade spring as $x = 0$ and the bottom as $x = l$ where $l$ is the length of the spring. The resonant frequency of the blade spring is then:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{R(\theta \sin \theta + \cos \theta - 1)}},$$  \hspace{1cm} (3)

where $\theta$ is the installation angle of the blade spring. We selected the parameters so that (i) the safety factor is greater than 3, (ii) the size to apply to the KAGRA OMC system is optimal, and
Figure 3. Left: Picture of zero vertical-horizontal coupling blade spring for the KAGRA OMC suspension. Right: Result of a transfer function analysis. We calculated the frequency response of the blade spring using ANSYS, the FEM engineering software.

(iii) it does not cause a horizontal motion to vertical motion at the working point. We reinforced the lateral width to meet the requirement of safety factor using a nonlinear FEM simulation and calculated the frequency response of the blade spring (see Fig. 3, right). Table 1 shows the final design values of the suspension system.

| Table 1. Parameter list of the KAGRA OMC blade spring |
|-----------------------------------------------------|
| Total mass  | 13 kg |
| Number of blade | 3 |
| Material     | MAS-1 |
| Yield stress  | 1.9 GPa |
| Young’s modulus | 182 GPa |
| Length       | 220 mm |
| Width        | 52.7 mm @bottom |
| Thickness    | 1.3 mm |
| Initial angle| 45 deg |
| Radius of blade | 190 mm |
| Working stress | 661 MPa |
| Resonant freq. | 2.23 Hz |

4. Summary and Acknowledgement
The OMC plays an important role in achieving the target sensitivity of KAGRA. In this proceeding, we described the optical and suspension design of the KAGRA OMC according to the requirement calculated with a modal model simulation using artificial mirror maps.

This work was supported by JSPS Specially Promoted Research 26000005, JSPS Core-to-Core Program, the joint research program of the ICRR, and the Mitsubishi Foundation. The authors would like to express our sincere appreciation to our colleagues in the LIGO group.

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