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# Design study and prototype experiment of the KAGRA output mode-cleaner

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**Abstract.** The sensitivity of the Japanese gravitational-wave detector KAGRA is limited mainly by quantum noise. In order to reduce the quantum noise level, KAGRA employs an output mode-cleaner (OMC), which filters out junk light to clean up the signal and the reference light at the signal extraction port. The proper design of the OMC is a key to achieve the target sensitivity of KAGRA. In this proceeding, we present two results. One is the final result of numerical simulations, from which we determined the optical parameters of the OMC. The other is the latest results of our prototype experiment, the goal of which is to establish the control scheme of the OMC.

## 1. Introduction

KAGRA is the Japanese second-generation detector based on a Michelson interferometer, with Fabry-Perot cavity in each arm (see Fig. 1) [1]. In addition, KAGRA has two optical resonators at the symmetric port and the anti-symmetric port, called the power-recycling cavity and the signal-recycling cavity. In order to maximize the observation range of gravitational waves from our primary target source *binary neutron stars*, the signal-recycling cavity length of KAGRA will be detuned from the resonance of the carrier light. KAGRA employs a homodyne readout scheme called *DC readout* [2], in which a fraction of the carrier light leaking to the dark port is used as the reference field to beat with the gravitational wave signals. The sensitivity curves and the observation ranges with different detune and readout phases have been compared to find a proper combination, which is a detune phase of 3.5 deg and the DC readout phase of 132 deg. The optimization of the readout phase is important in KAGRA where the sensitivity is limited by quantum noise.

## 2. Output mode-cleaner

### 2.1. Requirement

In this study, we assume 515 W of the laser power at the beam splitter. The radius of curvature of the test masses is 1.9 km and we assume a $\pm 1\%$ error between the two arm cavities. The arm cavity finesse is 1550 and the roundtrip optical loss is 100ppm. Here we also assume a $\pm 10\%$ loss imbalance between the two arm cavities. The roundtrip Gouy phase shifts, which describes interval of neighboring spacial modes of the carrier light, are 33 deg and 35 deg in the power and signal recycling cavities, respectively, and the incident angles at the folding mirrors in the recycling cavities are about 0.6 deg. The power reflectivity of the signal-recycling mirror is 85%.
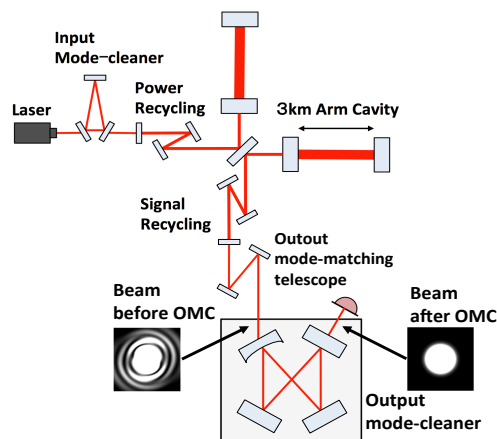
**Figure 1.** Schematic view of the KAGRA interferometer without mirrors for mode matching. The OMC, which consists of 4 mirrors (the first mirror is curved and the others are flat), is located at the anti-symmetric port where the gravitational-wave signal is extracted.

With these parameters, the power of the reference field at the dark port is about $1\,\mathrm{mW}$. A slight differential offset on the arm cavity lengths has been applied to obtain the proper readout phase. Compared with Advanced LIGO, the room-temperature gravitational-wave detector in the United States, which does not aim at optimizing the readout phase and has the reference field of about $40\,\mathrm{mW}$, KAGRA's requirement is more challenging. To realize the design sensitivity, our OMC must not degrade the shot-noise level by more than $5\,\%$ from that in the case with an ideal OMC. If the DC light power is $1\,\mathrm{mW}$, a possible breakdown of an acceptable degradation after the OMC is an follows; the signal loss is to be 2% or less, the residual spatial higher order modes are to be $10\,\mu\mathrm{W}$ or less, and the residual RF sidebands are to be $20\,\mu\mathrm{W}$ or less [3]. This requirement shall be satisfied by selecting a proper parameter set; namely, the finesse, round-trip Gouy phase shift and length of the OMC. In order to keep the signal loss being less than $2\,\%$, the finesse should be less than 800. It is important to select a proper combination of the Gouy phase and the cavity length, paying attention to the expected power in each higher order mode before the OMC, which should be numerically calculated using a simulation tool. In addition, we should consider the influence of the nanometer-scale surface errors of the test masses.

*2.2. FINESSE simulation*
In order to determine the design of the KAGRA OMC, we use a simulation tool *FINESSE*. FINESSE can analyze optical fields propagating in a user-defined interferometer not only with a plane wave approximation but also with the Hermite-Gauss modal expansion[4][5]. In the previous study of the KAGRA OMC performed by Ayaka Kumeta et al, phase maps of the test masses are introduced in the FINESSE code to simulate the expected beam distortions due to the nanometer-scale mirror surface errors [3]. A mirror phase map is an array of numbers representing the bump of the mirror surface. Since we do not have the actual mirror map of the sapphire test mass yet, those phase maps are numerically generated with the required power spectral density of the surface error taken into account.

We have modified some points of the previous simulation and obtained more accurate results. In KAGRA, the 10th mode comes out to the dark port the most since its distance to the neighboring resonance is as small as $6\,\mathrm{deg}$, which is the closest among the first 19 modes. Averaging the amplitude of each mode, we provide a typically mode-distributed beam and then multiply the OMC transmittance $T_{\mathrm{omc}}$ to each mode. The results are compared with different Gouy phases and OMC cavity length. We find that $\eta = 55.4\,\mathrm{deg}$ and $L = 75\,\mathrm{cm}$ is the most appropriate parameter set for the KAGRA OMC. As is shown in Table. 1 and Fig. 2, the higher order modes and RF sidebands are well suppressed with this design.
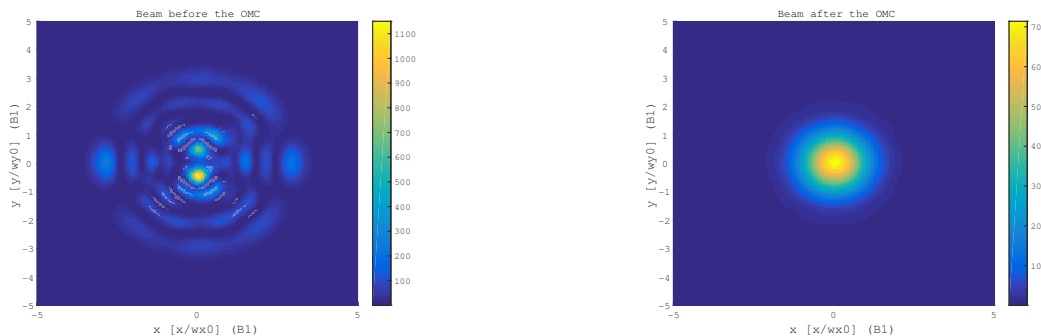
**Figure 2.** Beam profile of the before (left) and after (right) the OMC.

|  | 0th | 1st | 2nd | 3rd | 10th | RF |
|---|---|---|---|---|---|---|
| Before OMC | 1.38 mW | 333 μW | 6.57 mW | 1.10 mW | 26.1 mW | 357 mW |
| After OMC | 1.33 mW | 1.96 nW | 29.4 nW | 76.9 nW | 1.68 μW | 20.4 μW |

**Table 1.** The power in higher order modes and RF sidebands, before and after the OMC.
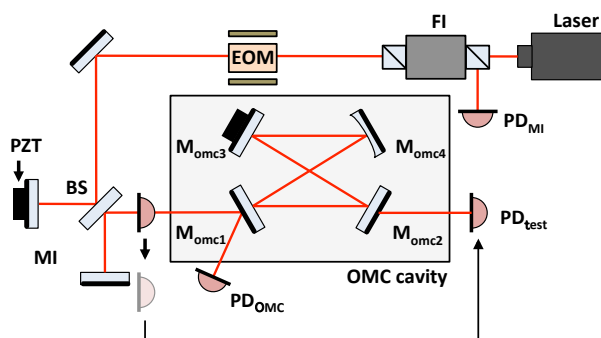
### 2.3. Prototype experiment



**Figure 3.** Schematic of the experimental layout. FI: Faraday isolator, EOM: electro-optical modulator, BS Beam splitter, MI: Michelson interferometer, PD: Photodetector. The fourth mirror ($M_{omc4}$) of the OMC is curved and the others are flat. PZT: piezo actuator attached.

We have constructed the prototype OMC at Tokyo Institute of Technology. The simplified experiment layout is shown in Fig. 3. The goal of this experiment is to establish the length control scheme and the parameters of this prototype are different from the actual KAGRA OMC. We use a 1064 nm Nd:YAG laser with 50 mW output power. The beam first transmits through a Faraday isolator and Electro-optical modulator that modulates the beam at 12 MHz and then is injected to a Michelson interferometer (MI). The MI is operated at its dark fringe using the Heterodyne readout technique with the reflected light extracted from the Faraday isolator ($PD_{MI}$) and the beam with up to 1.3 mW power is leaked to the dark port for the DC readout. The leaked beam comes into the OMC, which is a bow-tie cavity with 4 mirrors: the $M_{omc4}$ is curved and the others are flat, the radius of curvature of the $M_{omc4}$ is 2 m, the reflectivities $R_{omc1,4} = 0.98$, the $M_{omc2,3}$ are total reflection. We determined the cavity length to be 44 cm according to the size of our breadboard and chose the Gouy pahse of 38.7 deg

and the finesse of 150 based on the calculation results using a LIGO method [6]. The OMC length is locked to the resonance of the carrier light using Pound-Drever-Hall method with the reflected light from the $M_{omc1}$ ($PD_{OMC}$). With the MI being stably locked, we inject a signal at 2 kHz using a piezo actuator attached to one of the end mirrors of the MI. First we measure the output with the $PD_{test}$ before the OMC and obtain the noise spectrum. We then measure the output with the same PD but located after the OMC and obtain the noise spectrum. Both the MI and the OMC are locked during the measurement. The left panel of Fig. 4 shows the noise spectra before and after the OMC. One can see that the amount of the signal at 2 kHz after the OMC has decreased. This is partially because the large acoustic noise of the OMC has redistributed the signal field energy. The structure around the 2 kHz signal represents the up-converted acoustic noise at lower frequencies. We know that this is due to poor mounting of the piezo actuator of the OMC and will be replaced soon. The right panel shows the ratio of the two spectra that has been normalized to have the same amount of the 2 kHz signal. The plot shows a clear improvement of the signal-to-noise ratio above 1 kHz due to the OMC.
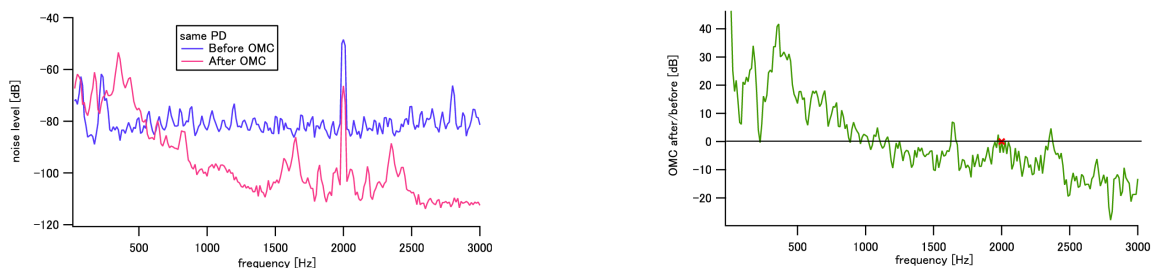


**Figure 4.** Left: Noise levels before and after the OMC. The amount of the signal at 2 kHz after the OMC decreases partially because of the upconverted noise around 1.7 kHz and 2.3 kHz. Right: Comparison of the signal-to-noise ratio before and after the OMC. The signal-to-noise ratio is improved above 1 kHz with the OMC. Red marker indicates the signal at 2 kHz.

## 3. Summary and Acknowledgement

The OMC plays an important role for KAGRA to realize the design sensitivity. The requirements of the KAGRA OMC is more challenging than other 2nd generation gravitational-wave detectors like advanced LIGO because of the low power of the DC light that is necessary to achieve the design sensitivity. In this proceedings, we modified the previous design to improve the performance of the OMC, We use a simulation tool FINESSE and numerically generated mirror maps. We also demonstrated in our prototype experiment that the signal-to-noise ratio is improved with the OMC.

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