

An arm length stabilization system with vertex injection of auxiliary lasers: a new scheme scalable to longer-baseline gravitational wave detectors

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19 September 2019

Abstract. Modern ground-based gravitational wave (GW) detectors require a complex interferometer configuration with multiple coupled optical cavities. Since achieving the resonances of the arm cavities is the most challenging among the lock acquisition processes, the scheme called arm length stabilization (ALS) had been

employed for lock acquisition of the arm cavities. We designed a new type of the ALS, which is compatible with the interferometers having long arms like the next generation GW detectors. The features of the new ALS are that the control configuration is simpler than those of previous ones and that it is not necessary to lay optical fibers for the ALS along the kilometer-long arms of the detector. Along with simulations of its noise performance, an experimental test of the new ALS was performed utilizing a single arm cavity of KAGRA. This paper presents the first results of the test where we demonstrated that lock acquisition of the arm cavity was achieved using the new ALS and residual noise was measured to be 8.2 Hz in units of frequency, which is smaller than the linewidth of the arm cavity and thus low enough to lock the full interferometer of KAGRA in a repeatable and reliable manner.

PACS numbers: 04.80.Nn, 95.55.Ym, 95.75.Kk, 07.60.Ly

Keywords: gravitational-wave detector, interferometer

Submitted to: *Class. Quantum Grav.*

1. Introduction

The first direct detection of gravitational waves (GWs) by the two LIGO detectors from a binary black hole merger in 2015 [1] marked the beginning of an era of GW astronomy. Moreover, the detection of GWs from a binary neutron star merger by the three LIGO-Virgo detectors [2], and many other electromagnetic follow-up observations [3] provided new insights into compact stars and their mergers. These observations of GW events have proved the importance of direct detection of GWs and detection with multiple GW detectors. It is planned that KAGRA joins the global GW detector network in late 2019 as the fourth detector [4]. It is expected that four-detector-observation enables us to improve the sky coverage of the localizable sources of GWs [4,5], to increase the network duty cycle, and to disentangle polarizations of GWs [6]. KAGRA has two unique features that the detector is built underground [7,8] and the key components, test masses that respond to GWs, are cooled down to cryogenic temperature [8,9]. These features will be of great importance for the next generation detectors [10,11]. Therefore intensive development of KAGRA is necessary not only for maximizing the science output of the four-detector network but also for paving the way towards the realization of the next generation detectors.

Currently all the GW detectors at sensitivities high enough to detect GWs are terrestrial laser interferometers. Although the working principle of such detectors is as simple as that of the Michelson interferometer, the real optical configurations of them are rather complex. In fact, the designed configurations of the main interferometers of Advanced LIGO, Advanced Virgo, and KAGRA employ multiple optical cavities. To properly operate the detector, all the cavities have to be controlled at their resonances.

Thus the control of the main interferometer is essential. Furthermore, it is necessary to have a tractable scheme to achieve the resonances of the cavities, or to acquire lock of the interferometer in other words, since it is inevitable for the interferometer to lose its lock by external disturbances such as earthquakes. However, the lock acquisition process is generally not straightforward, due to highly non-linear and cross-coupled response of the optical cavities to change in the cavity lengths [12, 13]. In particular, achieving the resonances of the arm cavities is most challenging because kilometer-long arm cavities come at a cost of very narrow frequency linewidth.

In order to achieve reliable and repeatable lock acquisition, a scheme called arm length stabilization (ALS) has been proposed [14], demonstrated [14, 15] and implemented in Advanced LIGO [16]. A similar scheme will be installed also in Advanced Virgo [17]. The scheme employs two auxiliary lasers that are phase-locked to the main laser of the interferometer, and the second harmonic generation (SHG) light of each auxiliary laser is used to control and stabilize the length of each arm cavity. With the ALS scheme, each cavity length can be kept at an arbitrary point with respect to the resonant points of the cavity. This makes it easy to acquire lock of the central part of the interferometer. Otherwise, control of the central part would be significantly disturbed or even broken due to the arm cavities stochastically passing across resonances. The SHG is used because use of different wavelength from that of the main laser enables us to utilize dichroic coating of mirrors. The finesse of the arm cavities are designed to be so low that achieving the resonance for the SHG light is easy. In addition, it is known that excess frequency noise introduced by the SHG is low enough [18].

KAGRA also adopts ALS as a part of the lock acquisition scheme. KAGRA uses two auxiliary lasers similarly but the control scheme is different by simplifying that of Advanced LIGO in a few aspects. In addition, the designed linewidth of the arm cavities is smaller than that of Advanced LIGO or Advanced Virgo, which may make lock acquisition of the KAGRA interferometer even more challenging. Therefore the detailed design and an experimental demonstration of the ALS scheme are crucial for the operation of KAGRA. In this paper, we report the control scheme of the ALS system of KAGRA, the design of the noise performance, and the results of the performance test utilizing a single arm cavity of KAGRA, where we successfully locked the arm cavity with the scheme.

2. Interferometer of KAGRA

Figure 1 shows a schematic view of the optical configuration of KAGRA. The optical configuration described here is similar to those of Advanced LIGO and Advanced Virgo, except that four test masses are cooled down to cryogenic temperature. The pre-stabilized laser (PSL) at a wavelength of 1064 nm is sent to a triangular optical cavity called the input mode cleaner (IMC). The transmitted light subsequently passes through a Faraday isolator in which the reflected beam from the main interferometer is extracted. The main interferometer is composed of four identical test masses (ETMX,

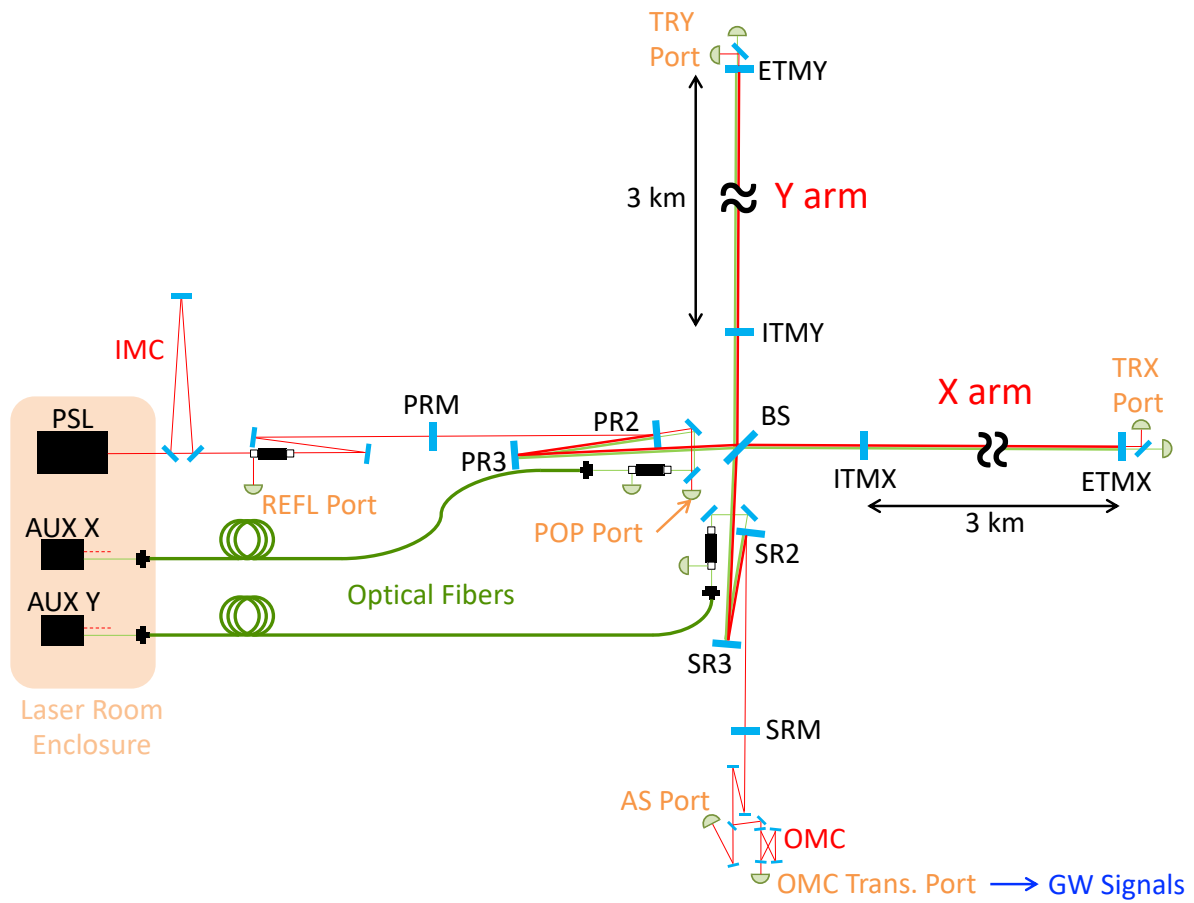


Figure 1. A schematic view of the optical configuration of KAGRA. A BS is placed at the center of the interferometer and separate the main laser beam into two arms, namely the X and Y arms. Each arm has a 3 km long cavity. Interference at the BS is controlled so that almost all the laser power is reflected back to the PRM. The detection ports for the control of the interferometer are also shown. Two dichroic auxiliary laser are placed in the laser room. Their green laser outputs are transferred to the center of the interferometer via optical fibers, and then injected to the main interferometer from the back side of PR2 or SR2. Refer to the main body for the detailed description.

ITMX, ETMY, and ITMY), a beam splitter (BS), three power recycling mirrors (PRM, PR2, and PR3), and three signal recycling mirrors (SRM, SR2, and SR3). Each pair of test masses, ETM and ITM, forms an arm cavity, and arm cavities are called the X and Y arms. The arm cavities and the BS form a Fabry–Perot Michelson interferometer (FPMI). The power recycling mirrors and both ITMs form a cavity called power recycling cavity, where the PRM resonantly reflects back the reflection from the FPMI to build up the laser power at the BS. Similarly, the signal recycling mirrors and both ITMs form another cavity called signal recycling cavity, where the SRM resonantly reflects back the transmission of the FPMI to change the detector response to GW signals so as to optimize the sensitivity of the detector. The transmission of the SRM, the output of the main interferometer, propagates through a bowtie cavity called the

Table 1. The five length degrees of freedom of the main interferometer of KAGRA.

DoF name	Description
DARM	the differential arm cavity length
CARM	the common arm cavity length
PRCL	the power recycling cavity length
SRCL	the signal recycling cavity length
MICH	the Michelson length

output mode cleaner (OMC). Variations in the optical power in transmission of the OMC corresponds to GW signals.

There are five length degrees of freedom in the main interferometer. The names and definitions of the degrees of freedom are summarized in Table 1. The information of displacement in each length degree of freedom is obtained at various detection ports. Error signal for CARM is obtained at the REFL port and error signal for DARM is obtained either at the AS port or the OMC transmission (trans.) port. CARM is sensitive to the frequency of the PSL and fluctuations of the resonant frequency of CARM is much more stable than those of the PSL frequency in general. The control of CARM is implemented by feeding the CARM signals back to the PSL frequency. In contrast, DARM is much less sensitive to fluctuations of the PSL frequency. So for the reason, the control signal is sent to the ETMs.

For the purpose of lock acquisition of the arm cavities, we have two auxiliary lasers in addition to the PSL in the laser room. Each auxiliary laser provides a pair of laser outputs: infrared and green. The infrared beam is the primary output and has a wavelength of 1064nm. The secondary one is the green laser which is frequency-doubled light of the primary beam, and thus has the wavelength of 532nm. The two green lasers are sent to the optical tables in the vicinity of PR2 or SR2 via optical fibers with the length of about 60 m. The green lasers are then injected to the main interferometer from the back side of PR2 or SR2. Because the PR2, SR2, and BS are dichroic and transmissive at 532nm, the green lasers injected from PR2 and SR2 are incident to the X and Y arms, respectively. The optical paths of the green lasers are slightly separated from that of the main laser owing to the wedged substrate and the dispersion of the BS and the ITMs.

3. Lock acquisition and ALS of KAGRA

3.1. Lock acquisition scheme

Our lock acquisition scheme is similar to that of Advanced LIGO [16]. It is divided into three steps as follows: (1) lock both arm cavities with the green lasers and keep the lengths of the arm cavities at an off-resonance point for the main laser with the ALS system, (2) lock the vertex interferometer (i.e. PRCL, SRCL, and MICH) and keep them locked using a combination of the interferometric signals that are less sensitive to

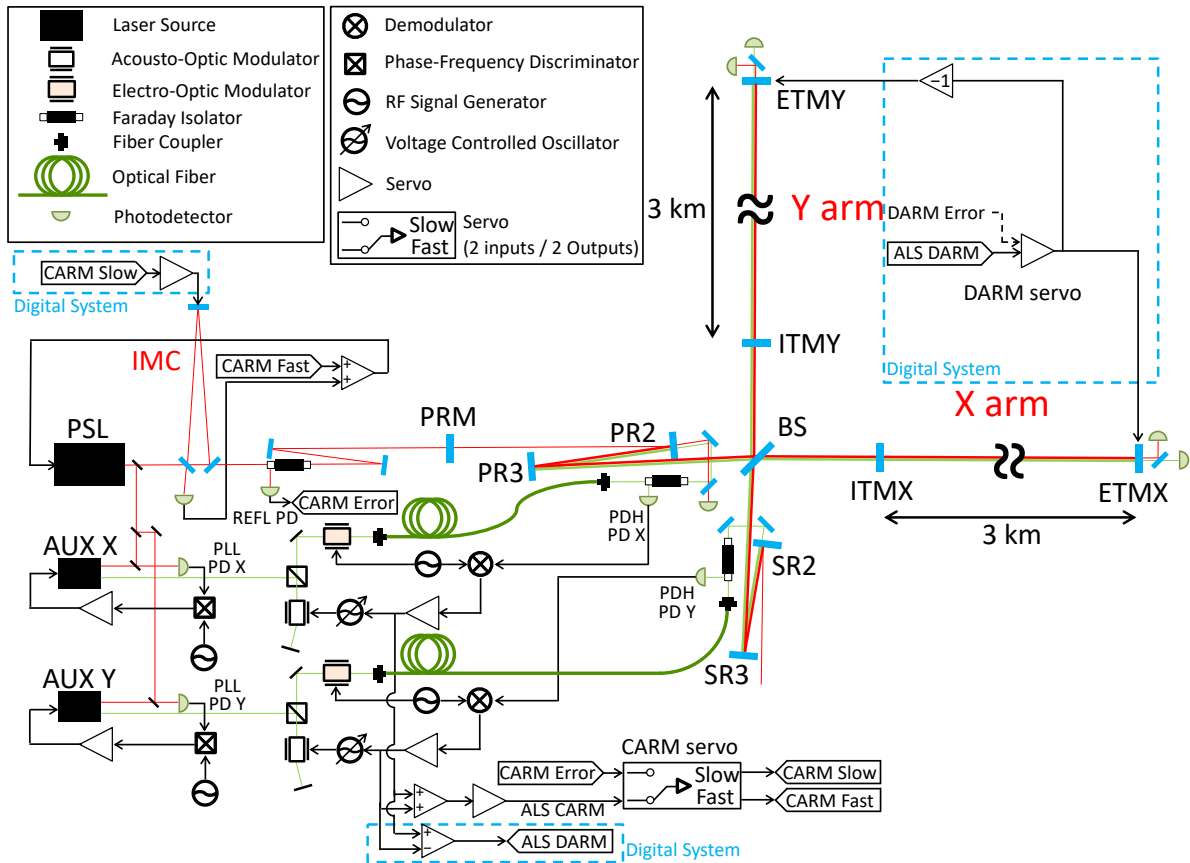


Figure 2. Overview of the arm length stabilization system of KAGRA. The frequencies of the two auxiliary lasers are phase-locked to that of PSL. The frequency of the each green laser is controlled by the combination of a double-path AOM and a VCO so that the green laser resonates in the corresponding arm cavity. The sum of the two control signals applied to the VCOs is used as an error signal of CARM (ALS CARM), and the difference of the two is used as an error signal of DARM (ALS DARM).

the carrier field of the main laser e.g., third harmonic demodulation signals [19] or beat note signals using sideband fields non-resonant in the main interferometer [20, 21], and (3) bring the arm cavity lengths to their resonances and switch the error signals of the arm length degrees of freedom to that obtained by using the carrier field of the main laser. In the step (3), the main laser frequency needs to be controlled with respect to the resonant frequency of the arm cavities with a precision better than the linewidths of the arm cavities, in order not to disturb the control of the three degrees of freedom of the vertex interferometer.

3.2. KAGRA-type ALS

The ALS of KAGRA is different from that of Advanced LIGO in their concepts, designs, and control strategy. KAGRA uses the green beams injected from the central area of

the interferometer, instead of the far end of the arm cavities. This made the control configuration simple by eliminating the long optical fibers along the kilometer-long arms. For comparison, let us summarize the features of the ALS of Advanced LIGO before describing the KAGRA ALS in detail. First, the SHG lasers are injected to the arm cavities from the end stations, areas around the end test masses. One auxiliary laser is placed in each end station. Second, small fraction of the main laser is sent to the end stations via optical fibers in order to stabilize the lasers in the end stations. Third, the differential mode of the two degrees of freedom of the arm cavity lengths is sensed using the beat note of the two SHG fields of the auxiliary lasers while the common mode is sensed using the beat note of one SHG field of the auxiliary laser and SHG field of the main laser.

The working principle of the KAGRA ALS can be summarized as follows. The two auxiliary lasers are phase-locked to the PSL with certain frequency offsets. The frequency of the green laser coming from each SHG output is locked to the corresponding arm cavity by using the combination of a double-path acousto-optic modulator (AOM) and a voltage controlled oscillator (VCO) as a frequency actuator. At this point, each control signal applied to the corresponding VCO is equivalent to the difference between the PSL frequency and the resonant frequency of the corresponding arm cavity assuming that the auxiliary laser is tightly locked to the PSL via the phase-locked loop (PLL). Therefore the sum of the two control signals works as an error signal for CARM, while the difference of the two works as an error signal for DARM. Let us call such error signals ALS CARM and ALS DARM. By feeding back ALS CARM and ALS DARM to the PSL frequency and arm cavity lengths, respectively, the main laser frequency is fixed to certain points with respect to the resonances of the arm cavities.

A detailed optical and control diagram of the KAGRA ALS is shown in Figure 2. For the phase lock of the auxiliary lasers, beat notes between the PSL and the auxiliary laser are detected by photodetectors (PLL PD X and Y). For this purpose, we chose silicon photodiodes, which have fast response but relatively low responsivity for 1064 nm laser, because we can easily have a lot of optical power on the photodiodes. The signals of the beat notes are demodulated at phase-frequency discriminators by mixing local oscillator (LO) signals from radio frequency (RF) signal generators. One can change the frequency offset between the PSL and the auxiliary laser by changing the frequency of the LO. Each demodulated signal is processed by an analogue filter circuit and then fed back to the frequency of the auxiliary laser via the piezoelectric transducer of the laser, accompanied with the laser temperature control for slow drift compensation. The green laser from each auxiliary laser is frequency-shifted by a double path AOM and successively phase modulation for the Pound–Drever–Hall (PDH) technique [22] is applied to it by an electro-optic modulator (EOM) in the laser room enclosure. Then the green lasers are injected to the X and Y arms from the back side of PR2 and SR2, respectively. The reflection from each arm cavity is picked off using a Faraday isolator and detected by a photodetector (PDH PD X or Y) to provide the PDH error signal. Each PDH error signal is filtered by another analogue circuit and fed back to a low-

noise VCO that generates RF signals driving the AOM. The control signals, the voltages applied to the VCOs, are used to obtain the ALS CARM and ALS DARM error signals. Because of the different control bandwidths, the CARM loop partially involves analogue control filters, while the DARM loop is entirely realized by a digital control. The control signals are added with each other and then low-passed in analogue filters to obtain the ALS CARM error signal whose frequency response is matched with the one for the main laser CARM signal (REFL CARM). The ALS CARM and the REFL CARM are sent to the same CARM servo board so that the input signals for the servo can be gradually switched. The servo has two output ports named slow and fast outputs, which are fed back to the IMC length and the error point of the IMC control loop, respectively, to form a dual loop control [23]. Meanwhile, for the DARM control, the two control signals driving the VCOs are sampled and digitally processed by real-time controllers and fed back to the differential motion of ETMs. Once the ALS CARM and ALS DARM loops are fully engaged, the resonant frequency of each arm cavity can be tuned to a desired value with respect to the frequency of the PSL by changing the frequency of the LO for the corresponding PLL. The features of the KAGRA ALS can be summarized in the following. The first feature is that two green beams are injected from the central area, as opposed to the end stations. Thanks to this feature, the necessary length of the optical fibers is not on the same order to the arm length but approximately 60 m, which makes it scalable to those with longer arm length such as the third generation detectors [10, 11]; fiber phase noise and optical loss do not increase as the arm length gets long. The second is that the configuration is simple in two aspects: less number of the sensors and less number of SHG setups. One possible drawback coming from this feature is that phase noise the lasers pick up as they propagate through the optical fibers directly becomes sensing noise of the ALS system. However, this issue is not critical because fiber phase noise is not too large since the fiber length is short. Additionally, the fiber noise cancellation technique [24] can be implemented independently if needed. The third feature is that the ALS CARM and ALS DARM signal are produced by summing the two signals from two arms in electronics or real-time controllers, respectively. This increases the flexibility of the ALS control loops.

3.3. Noise design of the ALS

In order to design the ALS system so that it has sufficiently low noise level for lock acquisition of the KAGRA interferometer, we simulated and designed the noise performance of the ALS. The noise design of the KAGRA ALS system is described here.

The primary noise requirement is that the root mean square (RMS) frequency fluctuations of the main laser with respect to the resonant frequency of one arm cavity is smaller than the linewidth of the arm cavity. This ensures smooth handing over from the ALS system to the main laser signals with a help of the signal derived from the optical power in transmission as done in Advanced LIGO [16]. In KAGRA, the

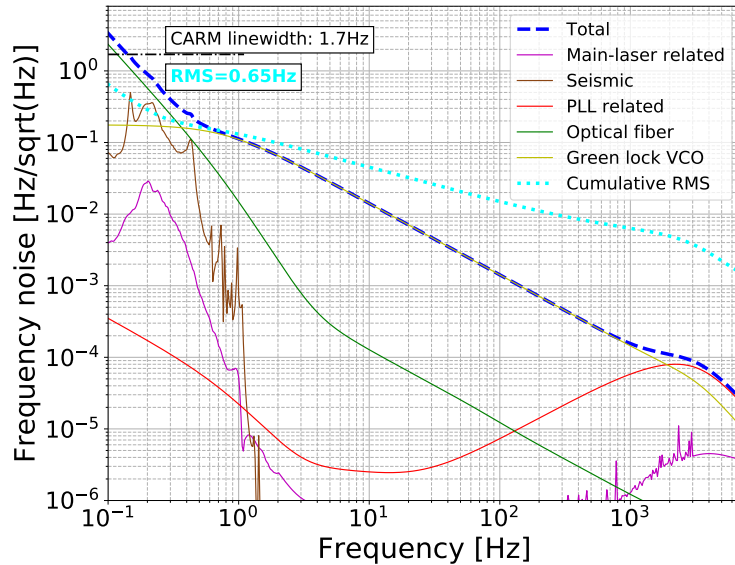


Figure 3. Amplitude spectral densities of simulated noises of the KAGRA ALS system. The blue dashed line shows total noise, which is quadrature sum of the contributions of all the noise sources considered in the design. The magenta trace shows the sum of the contributions of noises related to the PSL and its frequency stabilization. The brown line shows the estimated residual contribution of arm length fluctuations caused by seismic motion. The red trace shows the contribution of noises related to the PLLs of the auxiliary lasers including free-run frequency fluctuations of the auxiliary lasers. The green trace shows the contribution of phase noise caused by the optical fibers for the green lasers. The yellow trace shows the contribution of phase noises of the VCOs. The light blue dotted trace shows the cumulative RMS of the blue dashed trace integrated from the high frequency side.

designed value of the full width of an arm cavity is 33 Hz [20].

A more ambitious target can be given by the linewidth of the CARM cavity, which virtually serves as a single optical cavity corresponding to the CARM, with the full interferometer locked. If this condition is satisfied, the CARM control can be directly handed over from the ALS CARM to the REFL CARM. This will greatly simplify the arm locking process and contributes to increase the duty cycle of the detector. The full interferometer CARM linewidth is narrowed to 1.7Hz for KAGRA [20] due to the double cavity pole of the power recycling.

We numerically simulated and designed servo loops of the KAGRA ALS system in the frequency domain. The results of the simulated noise contribution to frequency fluctuations of the main laser with respect to the CARM resonant frequency are shown in Figure 3. The spectra have been computed by $[\Delta f_{\text{main}}(f) - \Delta f_{\text{CARM}}(f)]L(f; \kappa_{\text{CARM}})$, where Δf_{main} and Δf_{CARM} are the frequency of the main laser entering the main interferometer and the CARM resonant frequency, respectively, and $L(f; \kappa_{\text{CARM}})$ is a low-pass filter with a corner frequency of κ_{CARM} , the cavity pole frequency of CARM [25].

$L(f; \kappa_c)$ is defined as

$$L(f; \kappa_c) = \frac{1}{1 + if/\kappa_c}. \quad (1)$$

We adopt the spectra of $[\Delta f_{\text{main}}(f) - \Delta f_{\text{CARM}}(f)]L(f; \kappa_{\text{CARM}})$ because frequency fluctuations measured by the common mode of the arm cavities includes the effect from the cavity pole and its RMS has to be compared with the width of CARM. Figure 3 shows that the RMS of frequency fluctuations controlled by the ALS system is designed to be as low as 0.65 Hz, which is smaller than the width of CARM. The dominant noise source above approximately 1 Hz is expected to be frequency noise of the VCOs driving the AOMs. The dominant noise source below 1 Hz is expected to be phase noise of the green lasers introduced by the optical fibers. Fiber phase noise had been estimated based on a measurement of phase noise of an optical fiber of length of 5 m placed on an optical table. We scaled the measured level of phase noise in such a way that the power spectral density of phase noise of a fiber is proportional to the length of the fiber. We also confirmed that the primary target, which is the target for the single arm, can be achieved; the RMS of $[\Delta f_{\text{main}}(f) - \Delta f_{\text{ARM}}(f)]L(f; \kappa_{\text{ARM}})$ is 2.0 Hz and so smaller than the width of an the arm cavity, where Δf_{ARM} is the resonant frequency of an arm cavity and κ_{ARM} is the cavity pole frequency of the arm cavity.

4. Experiment with the X arm cavity

The performance of the KAGRA ALS system was evaluated with one of the arm cavities (the X arm). The single-arm setup allowed us for testing the control system for CARM. This is equivalent to the frequency stabilization control using the arm cavity as a frequency reference. In this section, the parameters of the arm cavity measured during this experimental period are additionally shown along with the design values after the overview of the setup of the experiment. Subsequently, the lock acquisition process of the arm cavity we demonstrated is explained. Finally, the results of the detailed analysis of noises of the ALS system are shown.

4.1. Set-up

Figure 4 shows the set-up for the length sensing and control of the X arm cavity during the experimental period. This experimental set-up was almost identical to the design shown in Figure 2. The differences were the following. Only the X arm was involved, and therefore the optics and electronics related to the Y arm were not involved. The PRM was intentionally misaligned. Unrelated laser beams were dumped so that they did not reach the signal recycling mirrors.

The optical power of the main laser incident on the IMC was set to approximately 270 mW. The laser power incident on the X arm was approximately 10 mW, after the partial transmission of the PRM (10 %) and the BS (50 %). The power of the green laser after the optical fiber was approximately 10 mW. The LO signal at about 40.0 MHz for

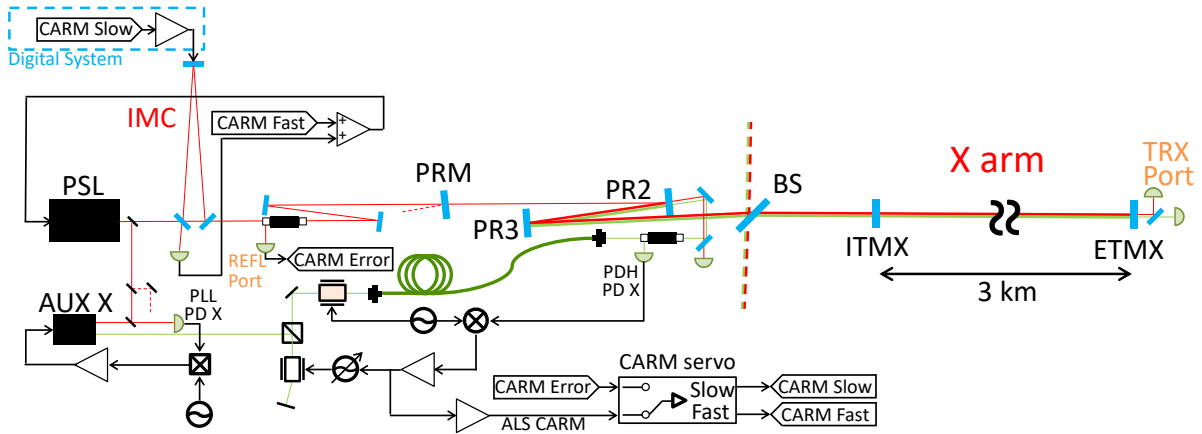


Figure 4. A schematic view of the configuration of the interferometer and the control for the X arm lock experiment. The PRM was misaligned, and the Y arm and the signal recycling mirrors were not involved in the experiment. The legend for the symbols in the figure can be found in Figure 2.

Table 2. Optical parameters of the X arm cavity. The values measured in the X arm experiment are shown along with the design values.

Parameter name	Designed	Measured
Cavity length ^a	3000 m [20]	2999.990(2) m
Finesse for 1064 nm ^b	1530 [20]	1410(30)
Roundtrip loss for 1064 nm ^{a,c}	< 100 ppm [20]	86(3) ppm
Mode matching ratio for 1064 nm ^a	–	0.91(1)
Transverse mode spacing ^a	34.80 kHz [20]	34.79(5) kHz
Finesse for 532 nm ^d	49.2	41.0(3)

Refer to the main body for the description of each measurement method. ^aMeasured by cavity scan; ^bMeasured by ring-down; ^cMeasured by the reflectivity of the cavity; ^dMeasured by the transfer function of the green lock loop.

the PLL was provided by a stable signal generator, E8663D from Keysight Technologies. The frequency of the oscillator for the PDH method of the green laser and the X arm was set to 33 MHz. The center frequency of the VCO was approximately 80 MHz. The PDH signal of the main laser and the X arm, which is labeled as “CARM Error” in Figure 4, was obtained by the demodulation of the signal of the photodetector at the REFL port at 45.0 MHz

4.2. Measured parameters of the X arm cavity

Table 2 summarizes the measured parameters of the X arm cavity. The cavity length, mode matching ratio of the main laser to the arm, and transverse mode spacing were measured by scanning the main laser frequency through free spectral ranges of the arm cavity utilizing the ALS system. The finesse for the main laser was measured

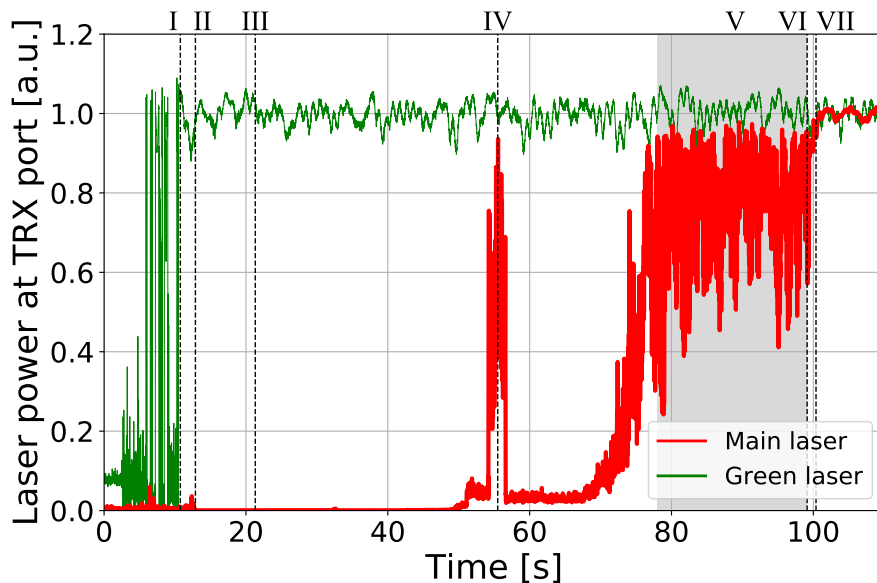


Figure 5. Laser power inside the X arm cavity during the lock acquisition process. The two traces show the time series plots of the laser power detected by photodetectors at TRX port, the transmission monitor port for the X arm. The red trace corresponds to the power of the main laser inside the cavity, and the green trace correspond to the power of the green laser inside the cavity. The labels from I to VII show the timings when the steps of the lock acquisition sequence switched from one to another.

by a ring-down method [26]. The roundtrip loss of the arm cavity was obtained by the measurement of the reflectivity of the cavity combined with the information from the cavity scan measurement [26]. The finesse for the green laser was obtained by the measurement of the open loop transfer function of the PDH lock loop.

4.3. Demonstration of the control handing-off

We achieved and demonstrated lock acquisition of the arm, where the error signal was handed over from the ALS CARM signal to the REFL CARM signal. Figure 5 shows how the power of the main and green laser at the TRX port evolved in time, along with the steps taken throughout the entire process. At point I, the resonance of the arm only for the green laser was achieved by locking the green laser frequency to the arm using the VCO only as an actuator. At point II, the feedback of the ALS CARM signal to the IMC length was turned on. From this point, the difference between the main laser frequency and the resonant frequency of the arm cavity was controlled via the ALS system so that no longer the main laser stochastically resonated in the arm. At point III, the ALS CARM control with the full frequency bandwidth using both slow and fast outputs of the CARM servo was engaged. The difference between the main laser frequency and the resonant frequency of the arm cavity was gradually tuned by sweeping the LO frequency of the PLL. At point IV, the position of the resonance of the arm cavity was spotted in terms of the LO frequency. In the shaded area labeled

as V, the main laser was kept at a resonant point via the control by the ALS system. We stayed for approximately 20 seconds in this stage for the purpose of demonstrating the stability of the ALS system. At point VI, the input of the CARM servo for “CARM Error” was enabled to start the hand-over of the control paths. At point VII, after 1 second from point VI, the input of the CARM servo from the ALS CARM signal was disabled to finish the hand-over. Consequently, lock acquisition of the main laser to the X arm was achieved. These lock acquisition processes did not fail unless the control of the green laser frequency to the arm lost its lock. Since the duration of lock of the green laser frequency to the arm was typically a few hours, it can be said that the processes were reliable. We tested these processes several times on different days, and succeeded in achieving lock acquisition of the main laser to the arm every time in the same way. This result clearly shows that the performance of the ALS system was demonstrated and the lock acquisition scheme of an arm cavity with it was established.

4.4. Noise budget of the ALS of the X arm

We also conducted a set of measurements to characterize the noise sources of the ALS system since characterizing the noise performance of the ALS system is helpful for improving the ALS system.

To evaluate residual frequency fluctuations of the PSL with respect to the arm cavity, we locked the main laser frequency to the X arm with “CARM Error” used as an error signal while the frequency of the green laser injected to the X arm was also locked to the X arm without feeding any signals back to the main laser or test masses. In this configuration, sensing noise of the ALS system can be inferred by measuring the ALS CARM signal under the assumption that residual frequency fluctuations of the main laser with respect to the X arm is small enough to be ignored for the noise estimation. We adopted this evaluation method to suppress the nonlinear effect in “CARM Error”, instead of a straightforward method where one measures the amplitude spectral density (ASD) of the “CARM Error” signal while the PSL frequency is controlled to the resonant frequency of the arm so that the “CARM Error” signal is kept around the zero point. The straightforward method may suffer from the nonlinear effect in the “CARM Error” signal if it is not confined sufficiently close to the zero point.

The results of the ALS sensing noise are shown in Figure 6. The black trace shows the measured ASD of the ALS sensing noise calibrated to $[\Delta f_{\text{main}}(f) - \Delta f_X(f)]L(f; \kappa_X)$, where Δf_X is the resonant frequency of an arm cavity and κ_X is the cavity pole frequency of the arm cavity. The grey dotted trace shows the cumulative RMS of the black trace integrated from the high frequency side. The RMS was measured to be 8.2 Hz, which is smaller than the primary requirement, i.e., the linewidth of the X arm cavity. This indicates that the ALS system was sensitive enough to hold the main laser within the resonance width of one arm cavity, as is consistent with the time series shown in the previous section. Note that here we used the measured parameters of the cavity described in Section 4.2.

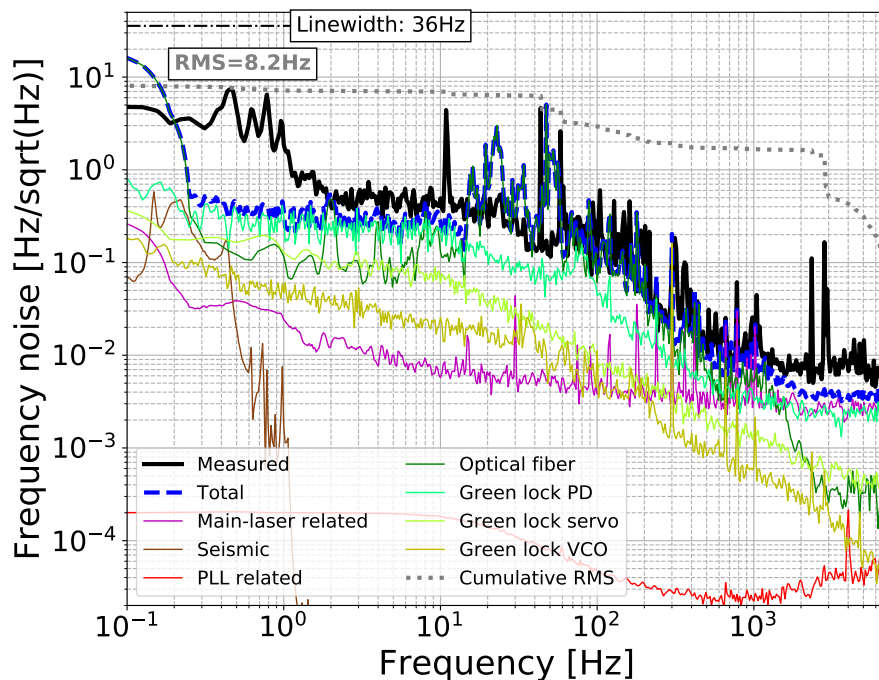


Figure 6. A noise budget plot of sensing noise of the KAGRA ALS. The black trace shows the measured ASD of sensing noise of the ALS, calibrated to $[\Delta f_{\text{main}}(f) - \Delta f_{\text{X}}(f)]L(f; \kappa_{\text{X}})$. The grey dotted trace shows the cumulative RMS of the black trace from the high frequency side. The blue dashed line shows total noise, quadrature sum of the contributions of all the known noise sources described in the following. The magenta trace shows the sum of the contributions of noises related to the PSL and its frequency stabilization. The brown line shows the estimated residual contribution of arm length fluctuations caused by seismic motion. The red trace shows the contribution of noises associated with the PLL of the auxiliary laser including free-run frequency fluctuations of the auxiliary laser. The green trace shows the contribution of phase noise caused by the optical fiber for the green laser. The light green trace shows the contribution of noise of the photodetector circuit to obtain the PDH signal of the green laser. The yellow-green trace shows the contribution of noise of the servo circuit for the feedback to the VCO. The yellow trace shows the contribution of phase noise of the VCO.

In order to investigate the origin of measured sensing noise of the ALS system, we made a number of supplemental measurements to estimate the contributions of the various noise sources as shown in Figure 6. The blue dashed line shows total noise, which is quadrature sum of the contributions of all the considered noise sources. In the frequency band approximately between 10 Hz and 1000 Hz, phase noise caused by the optical fiber for the green laser limited total noise. It shows a good agreement with measured sensing noise. In contrast, there is discrepancy between total and measured noise at low frequencies below 10 Hz. This indicates there were noise sources that are not taken into account.

5. Discussion

5.1. Noise sources

Let us discuss here the implications of the noise analysis shown in Figure 6. Comparing Figures 3 and 6, it is clear that we had underestimated the fiber phase noise. This probably came from the difference of the environment between the KAGRA site and the fiber testing setup. The optical fibers in KAGRA were laid on cable racks and the wall of the laser room enclosure and suffer from vibration and air flow. Since it is known that phase noise caused by an optical fiber can be largely suppressed by a fiber noise cancellation technique [24], we can suppress this noise by implementing such a technique if further improvement of the noise performance is required.

The possible noise sources that might account for the discrepancy between total and measured noise at low frequencies below 10 Hz are the couplings from the motion of the suspended optics. We observed significant coherence between measured sensing noise of the ALS system and the longitudinal motion of PR2 sensed by its local sensors [27] at the peak at 0.45 Hz. PR2 reflects the main laser but transmits the green laser. Its longitudinal motion must have caused Doppler shift only in the frequency of the main laser. The amount of the PR2 motion sensed by the local sensors was $0.85 \mu\text{m}/\sqrt{\text{Hz}}$ at 0.45 Hz. Since the amount of the Doppler shift can be expressed as $2v/\lambda$, where v is velocity of the mirror and λ is wavelength of the main laser, the Doppler shift caused by PR2 is estimated to be $4.5 \text{ Hz}/\sqrt{\text{Hz}}$, which is comparable to the peak height in the sensing noise at 0.45 Hz. Similarly, the motion of the steering mirror behind PR2 which is installed on a suspended breadboard might have introduced Doppler noise because this mirror is relevant only to the green laser. Unfortunately, there was no direct way to prove it because we had no sensors for the motion of this mirror. However, the amount of its motion can be estimated from the level of the seismic motion. The velocity of the seismic motion was approximately $4 \times 10^{-7} \text{ m/s}/\sqrt{\text{Hz}}$ at 0.25 Hz and $1 \times 10^{-8} \text{ m/s}/\sqrt{\text{Hz}}$ at 1.0 Hz. Assuming that the amount of the motion of the steering mirror is on the same order of the seismic motion, the amount of the Doppler shift caused by the steering mirror can be estimated to be approximately $0.8 \text{ Hz}/\sqrt{\text{Hz}}$ at 0.25 Hz and $0.02 \text{ Hz}/\sqrt{\text{Hz}}$ at 1.0 Hz. These numbers are smaller than the level of the measured ASD of sensing noise by a factor of 4 to 100. Therefore, it is not likely that the Doppler shift caused by the steering mirror limited the noise performance unless the seismic motion was enhanced by the suspended breadboard. We need further investigation on the discrepancy in any case.

5.2. Towards lock of the full interferometer

Next, we discuss the demonstrated performance of the ALS system in the context of the full interferometer of KAGRA. As mentioned in Section 3.3, the measured RMS of the ALS sensing noise was well within the primary requirement (33 Hz). Therefore, assuming that we can achieve the same noise performance of the ALS system also for the Y arm,

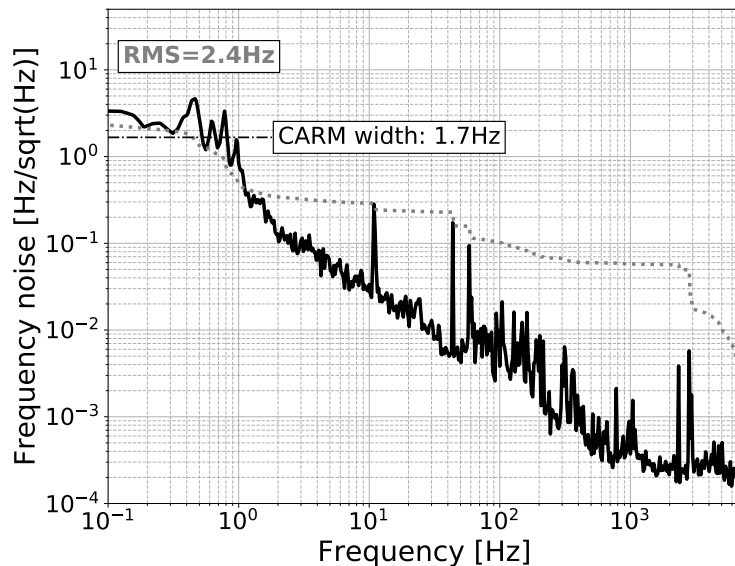


Figure 7. The expected spectrum of the ASD of $[\Delta f_{\text{main}}(f) - \Delta f_{\text{CARM}}(f)]L(f; \kappa_{\text{CARM}})$, calculated from measured sensing noise of the ALS of the X arm. We assumed that sensing noises of the ALS of the X and Y arm are independent. The grey dotted trace shows the cumulative RMS of the black trace from the high frequency side.

we will be able to lock the full interferometer using the ALS system with a help of the arm transmission signals [16]. Keeping the same assumption, we expect that the RMS of $[\Delta f_{\text{main}}(f) - \Delta f_{\text{CARM}}(f)]L(f; \kappa_{\text{CARM}})$ will be 2.4 Hz (Figure 7). Figure 7 indicates that we need to improve the noise level of the ALS system in the frequency band lower than approximately 1 Hz to satisfy the more ambitious target, which is that the RMS of $[\Delta f_{\text{main}}(f) - \Delta f_{\text{CARM}}(f)]L(f; \kappa_{\text{CARM}})$ is smaller than the full width of the CARM cavity. Although the current noise performance does not satisfy the more ambitious target, a previous work [28] suggested that a self-amplification process of the PDH signal might enable us to hand over the control paths directly from the ALS CARM to the REFL CARM signal, even if frequency fluctuations are larger than the linewidth. Achieving direct lock of CARM with the ALS system for the first time is a future work.

6. Conclusion

We designed a new type of the ALS system for KAGRA. It is scalable to the GW detectors even with longer arms such as the ones planned in the third generation detectors, thanks to the vertex injection of the green lasers to the arms. The detailed noise design of the ALS showed that the ALS can potentially enable us to directly hand over the CARM control from the ALS CARM to the PDH signal of the main laser of CARM, which will simplify the lock acquisition process. Utilizing the X arm cavity, the performance of the new ALS was tested and characterized as follows. (1) Lock acquisition of the arm cavity through the hand-over from the ALS CARM to the PDH

signal of the main laser were demonstrated. (2) The noise characterization of the system showed that the RMS of $[\Delta f_{\text{main}}(f) - \Delta f_X(f)]L(f; \kappa_X)$ reached 8.2 Hz, with $\Delta f_{\text{main}}(f)$ controlled by the ALS system. The RMS was well within the linewidth of the single arm cavities (33 Hz) and thus the noise performance should be sufficient for lock acquisition of the full interferometer of KAGRA. These results show that the new ALS system has been experimentally established.

Acknowledgments

This work was supported by MEXT, JSPS Leading-edge Research Infrastructure Program, JSPS Grant-in-Aid for Specially Promoted Research 26000005, MEXT Grant-in-Aid for Scientific Research on Innovative Areas 24103005, JSPS Core-to-Core Program, A. Advanced Research Networks, the joint research program of the Institute for Cosmic Ray Research, University of Tokyo, National Research Foundation (NRF) and Computing Infrastructure Project of KISTI-GSDC in Korea, the LIGO project, and the Virgo project.

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