Final Design and Implementation of the KAGRA green lock system

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Contents

1 Overview

1.1 Overview of this document

This document summarizes the design and current implementation of the green lock (GRE) system or ALS (Arm Length Stabilization) system as a snapshot. For historical reasons, we refer this particular system either ALS system or green lock system, interchangeably.

1.2 Notes on version updates

This document is version 2, meant for capturing the latest implementation as of June 2021.

1.3 Scope of this document

The scope of this document covers the following items.

- Design concept and associated considerations
- Final design and actual implementation
- Lessons learned

The performance achieved by the actual implementation is not described in this document. Please refer to Refs. [2, 3, 4] and references therein.

2 Related documents and development history

2.1 Related documents

[1] "Document Tree for Arm Length Stabilization System," JGW document, JGW-E1807769, Link to JGW-E1807769

[2] R. Sugimoto, "Development of Auxiliary Locking System in Gravitational Wave Telescope KAGRA," Master thesis, Univ. Toyama (2020) Link to JGW-P2012605

[3] Y. Enmoto *et al.,* journal paper in preparation (2019)

[4] K. Yokogawa, "Arm length stabilization system in KAGRA," (in Japanese) master thesis, Univ. of Toyama (2019) Link to JGW-P1909919

[5] Y. Enomoto, "Modification of RFPD for Green Lock PDH," klog 5735, (2018), Link to klog 5735

[6] Y. Enomoto, "Proposal: Modification of LSC RFPD for Green PDH," JGW-D1808442-v1 (2018) JGW-G1808442-v1

[7] Y. Enomoto, "Prototype Low Noise VCO Chassis Top Assembly," JGW–D1808968 (2018), JGW–D1808968

[8] K. Izumi et al., "ALS/PSL installation update: fibers are successfully pulled," klog 5785 (2018), Link to klog 5785

[9] "[CONFIDENTIAL] ALS optical fiber routing," (in Japanese) JGW-D1813050 (2018) Link to JGW-D1813050

[10] K. Yokoagaw and Y. Moriwaki, "Material for the review about green laser (2018.Mar.28),' JGW-T180103-v3 (2018 Link to JGW-T180103

[11] K. Doi *et al.,* "ALS meeting material (2017.Nov.13)," JGW-E1707416-v1 (2017) Link to JGW-E1707416

[12] Y. Michimura, "Arm length stabilization conceptual design," JGW-T1605353-v12 (2016) JGW-T1605353

[13] D. Tatsumi *et al.,* "Servo designs for green lock, " in Japanese, JGW-T1200788-v1 (2011) JGW-T1200877

[14] K. Izumi, "Landing point for the messenger wire for pulling the GRE fibers," (2018) JGW-G1808535-v1

[15] Y. Michimura, "ALS Sideband Frequency", T1605626-v3 (2018) JGW-T1605626-v3

2.2 Brief history

2.2.1 Conceptual design phase (2011-2016)

The conceptual design was initiated in 2011 by Tatsumi [13] with input from K. Arai. Several main features were already introduced, such as the use of the Prometheus lasers, injection of the green light from the corner volume and the use of an AOM to lock green light to an arm cavity. Further study had been carried out by the group in the University of Toyama and the KAGRA MIF team since 2016. The studies include experimental verifications, fiber selection and circuit designs based on the conceptual design [12].

2.2.2 Implementation phase (2017-2019)

Later in 2017, the team proceeded with the implementation designs as well as procurement where the design of the optical layouts and hardware parts began being consolidated. In August 2017 and March, 2018, the team underwent review processes where the installation route of the fibers and the fiber selection were identified as main concerns.

2.2.3 Upgrade phase 2021

The fiber noise cancellation loops were upgraded.

3 Conceptual Designs

3.1 Role of the green lock system

The ALS system shall be able to control the resonance conditions of the arm cavities with respect to the infrared science laser independently of the resonance condition in the central dual-recycled Michelson interferometer. The ALS serves as extra sensors and controllers to make the lock acquisition process much less stochastic.

3.2 Requirements

The ALS system shall have the following functions.

- Sensing the displacement of the arm cavities[1] for a sufficiently wide range
- Controlling the length of the arm cavities and laser frequency at a precision level required for lock acquisition.
- The sensing and control must be insensitive to the resonant condition of the dual-recycled Michelson interferometer.

In order to achieve a repeatable process in lock acquisition, we set the following requirement values for the ALS system.

- Range for controlling each of the cavity length shall be greater than XXX m.
- Precision for controlling each cavity length shall be YYY nm in root mean square (rms).

3.3 Architecture

A simple diagram will be here.

3.3.1 RF modulation frequencies

The sideband frequencies are selected to be 32 and 33 MHz. See [15].

3.4 Difference against aLIGO

The biggest difference is that the auxiliary lasers are injected from the corner volume as opposed to the injection from the end stations. This choice completely removes the need for kilometer-long optical fibers.

Another difference is that the signals for cavity lengths are extracted electronically as opposed to the one via optical beatnote measurements. The electronic signal extraction is less involved in terms of the optical setup while no drastic improvement or degradation in the noise performance is expected compared against the aLIGO scheme.

[1] or equivalently, relative shift in the frequency of science laser.

Parameter	Value	Notes
ITMs		
Transmission for 532 nm	0.06 +0/-0.005	larger than ETM for 532 nm
Asymmetry in transmission for 532 nm	No requirement	
HR loss for 532 nm	$< 1\%$	
AR reflectivity for 532 nm	$< 5\%$	as small as possible
ETMs		
Transmission for 532 nm	0.06 +0/-0.005	smaller than ITM for 532 nm
Asymmetry in transmission for 532 nm	No requirement	
HR loss for 532 nm	$< 1\%$	
AR reflectivity for 532 nm	$< 5\%$	as small as possible

Table 1: Coating specifications for the test masses

4 Final design and Implementation

4.1 Test mass coatings

4.1.1 Specification

The coatings of the test masses are designed such that high reflectivity is achieved for both 532 and 1064 nm. The lower finesse is for 532 nm, the easier resonance acquisition becomes. However, if the finesse was too small, it would introduce the spurious coupling of the TEM01/10 and other higher odd-number order modes into the TEM00 modes, leading to degraded performance in control precision. For this reason, the nominal finesse value was targeted to be approximately 50. The specification calls for the values shown in table 1. The complete set of design parameters are available in JGW wiki at `http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/LCGT/subgroup/ifo/MIF/OptParam`.

4.2 Lasers

4.2.1 Specifications

The two lasers are both *Prometheus-532-100-CP* from Coherent Inc. The output power for the 532 nm light is 100 mW.

The lasers in the GRE must to produce the second harmonic fields of the main science laser at 1064 nm. In order not to use significant amount of the optical power out of the main laser, we chose to use independent lasers radiating the 1064 nm laser light. The cost of this scheme is that we must introduce the phase-locked loop system to tie the frequencies of the GRE lasers to the main one.

Description	Laser S/N	Diode current	Xstal temperature
Prometheus for ALS X	2143A	2.05 A	23.51 deg
Prometheus for ALS Y	2143B	2.20 A	22.42 deg
Prometheus for spare	7023	2.01 A	–

Table 2: A summary of the Prometheus lasers currently installed. Both lasers receive power voltage from the UPS unit.

4.2.2 Implementation

Laser units— Three Prometheus lasers were purchased; two for the actual use in KAGRA and the other for spare and prototyping. As of writing, the spare unit is in the University of Toyama for carrying out extra experiments. The part numbers for the two lasers installed in the PSL room are summarized in the table below.

UPS unit— In addition, a UPS unit was installed in Jan. 2019 for supplying stable power voltages for the two lasers. The UPS unit is SMT1500RMJ2U from APC. The UPS unit resides in the same electronic rack as the laser controllers.

Temperature settings—The temperature settings for the laser crystals were carefully adjusted such that the frequency difference of each GRE laser with respect to the science laser is 80 MHz. The absolute wavelengths as functions of the crystals' temperatures are summarized in figure 1. The PLS runs nominally at a crystal temperature of 46.4 deg as noted in the IOO manual (JGW-T1808998-v3).

4.3 Optical fibers

4.3.1 Specifications

To deliver the green light onto the POP and POS tables, two fibers with different lengths are necessary. The lengths for these fibers are summarized in table 3. Taking the advantage of this installation opportunity, we decided to install the IR fibers too for future use.

As for the fibers for the 532 nm wavelength, the below is a list of the common specifications.

- Wavelength: 532 nm
- End caps: 330+/-30 μm long end caps (at the both ends)
- Sheath: ϕ 3 mm OD Doplex Zipcoard tubing
- Fiber type: Nufern PM-S405-XP
- End connectors: FC/APC, narrow key

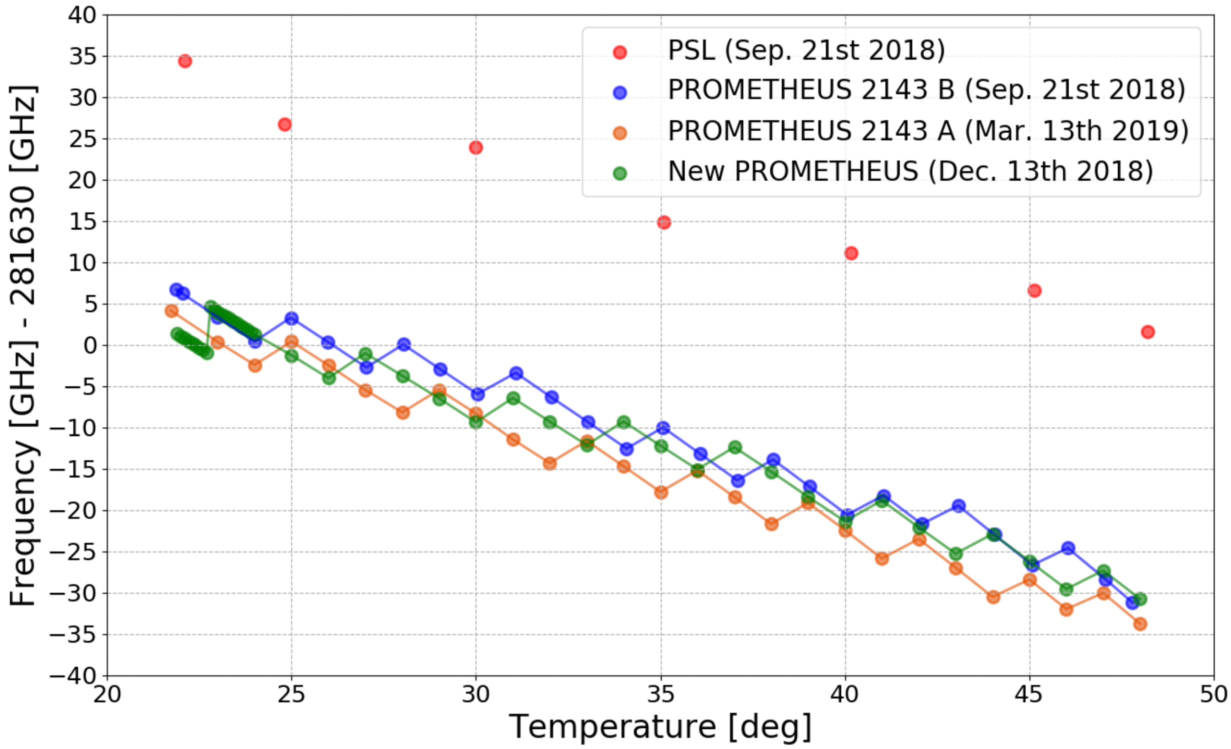

Figure 1: Measurement of absolute frequencies as functions of the crystal temperature. The measurement was done in 2018 and 2019. "New Prometheus" shown as green dots are the spare unit.

- Connector key: Slow axis

The fiber ends are protected by the end caps in order to reduce the risk of damaging the end parts in case high optical power was applied to the fibers. The minimum required power for 532 nm was set to XXX mW. Each fiber has a duplication fiber and they are collectively assembled as a single bundle, called duplex, for redundancy.

As for the fibers for the 1064 nm, the below is a list of the common specifications.

- Wavelength: 532 nm
- End caps: N/A
- Sheath: ϕ 3 mm OD Doplex Zipcoard tubing
- Fiber type: Nufern PM-S405-XP
- End connectors: FC/APC, narrow key
- Connector key: Slow axis

Descriptions	fiber P/N	Fiber length	# of fibers
PSL-POP table fibers for 532 nm	Nufern PM-S405-XP	58 m	2 (Duplex cable)
PSL-POP table fibers for 1064 nm	Nufern PM980-XP	58 m	2 (Duplex cable)
PSL-POS table fibers for 532 nm	Nufern PM-S405-XP	63 m	2 (Duplex cable)
PSL-POS table fibers for 1064 nm	Nufern PM980-XP	63 m	2 (Duplex cable)

Table 3: A summary of the Prometheus lasers currently installed. Both lasers receive power voltage from the UPS unit.

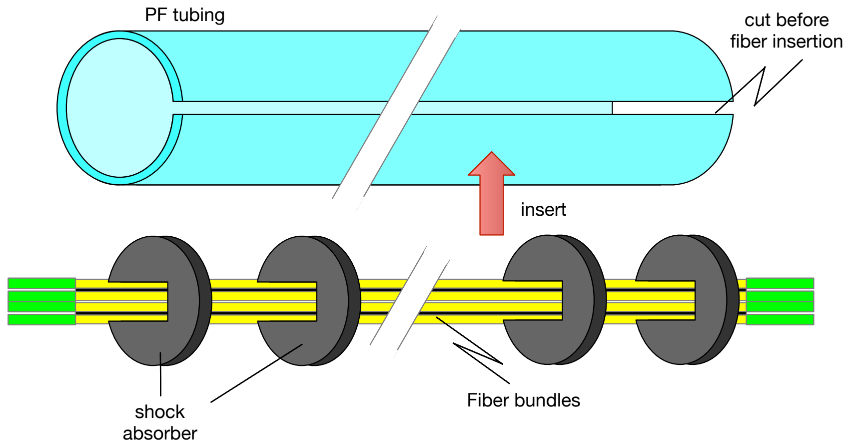

Figure 2: An illustration of the PF tubing for protection. The shock absorbers are placed approximately ever 1 meter or so.

4.3.2 Implementation

Bundles of the optical fibers were installed on August 11th in 2018 by Fujitsu Fsas Inc. [8].

Fiber protection— To protect the fibers from water and other possible corrosion materials, the fibers in the experimental area are put in PF tubing (Plastic Flexible Conduit tubing). Figure 2 shows an illustration of how it was implemented. Figure 3 shows a picture of the actual work done by Fujitsu Fsas. The portion, that are in the PSL room and the clean area around PR2 and SR2 areas, do not have the PF protection. In addition, in order to stably hold the fibers within the PF tubing, shock-absorbing material[2].

Fiber routing— The routing paths were decided based on the discussion with the industrial contractor. Details can be found in Refs. [9, 14].

Fiber core transmission tests— Table 4 summarizes the transmission tests performed right after the completion of the installation to confirm that the fibers did not have any damage [8]. The measurements were done only for the fibers for 532 nm and we did not

[2] A spongy material – the details not specified or confirmed.

Figure 3: A picture of the fiber installation work around the PR2 chamber in August, 2018. The yellow cables are the optical fibers being inserted into the light blue PF tubing. The black spongy materials are attached to the optical fibers before the insertion.

Fiber	**Output**	**Core trans.**	**Trans. ratio**
CCH-948-63 A (63 m duplex fiber, A)	27 mW	66%	110%
CCH-948-63 B (63 m duplex fiber, B)	22 mW	54%	105%
CCH-948-58 A (63 m duplex fiber, A)	24 mW	59%	87%
CCH-948-58 B (63 m duplex fiber, B)	25 mW	61%	90%

Table 4: A summary of the core transmittance tests. The input light power was 68 mW in this measurement. The coupling efficiency was assumed to be a typical value of 60%. The transimittance ratio is defined as the ratio of the output power after the installation over the one before the installation.

evaluate the core transmittance for the 1064 nm fibers.

4.4 Low-noise voltage controlled oscillators

4.4.1 Specification

The low noise VCOs (voltage controlled oscillators) are required for driving the AOMs with sufficiently low frequency noise. The tentative specification was set such that the unit essentially duplicates the architecture for aLIGO's low noise VCOs (LIGO-E1200120-x0) where a tunable oscillator signal is mixed with stable seed RF signal.

4.4.2 Implementation

See the top assembly document [7] and related documents therein. This unit is meant to be prototype in the sense that the noise performance has not fully understood. Two units were made and installed.

4.5 Phase-Frequency Discriminator

4.5.1 Specification

The tentative specifications are set such that the phase frequency discriminator achieves the readout noise as good as that built for aLIGO (LIGO-D1002476). The architecture is essentially the same — the combination of AD96687 and AD9901 for phase-frequency discrimination.

4.5.2 Implementation

The unit was designed, assembled and tested in the University of Toyama. See the documents listed below for the details.

4.6 AOM

4.6.1 Specifications

The AOM is necessary to continuously control the laser frequencies of the 532 nm light for keeping the green light resonating in the arm cavities. AOMO 3080-125 from Gooch and Housego was selected for the AOMs.

4.6.2 Implementation

Two units are installed in the PSL optical bench — one for ALS X and the other for ALS Y. Currently the mounts are temporary ones and could be replaced with a dedicated block-mount made by University of Toyama.

4.7 EOM

4.7.1 Specification

EO-T30M3-VIS fro Qbig was chosen for the EOM.

4.7.2 Implementation

Similarly to the AOMs, the current mounts can be replaced with a more rigid mount if necessary.

4.8 Mirror holders

TBW.

4.9 Small optics

TBW.

4.10 In-vac oberisks

TBW

4.11 Photodetectors

4.11.1 The beatnote photodetectors

818-BB-21A was selected for the photodetectors monitoring the beatnote.

4.11.2 The PDH photodetectors

The units were custom-made RFPDs (JGW-D1201280) with manual adjustments applied on the circuit. A set of modifications is applied to the existing PCB including the replacement of the photodiode with a Hamamatsu S3399 and adjustment of LC network [6]. In addition, the removal of the C31 capacitor was necessary [5].

The units currently in use are:

- JGW-S1808690-v1 for the X arm, tuned for 33 MHz.
- JGW-S1808567-v1 for the Y arm, tuned for 32 MHz.

4.12 Picomotors

TBW

4.13 Realtime digital system

4.13.1 Signal I/Os

4.13.2 Guardians for automation

5 Lessons learned

5.1 Fiber vibration noise

5.2 AC100V power supply

5.3 VCO offset