Interferometer Locking Scheme for Advanced Gravitational-Wave Detectors and Beyond

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Abstract Among the lock acquisition process, achieving the resonances of the arm cavities is particularly challenging because kilometer-long arms make their linewidths narrow. In the third generation detectors, which will have longer arms with narrower linewidth, the lock acquisition process will be even more challenging. In lock acquisition of Advanced LIGO, a scheme called arm length stabilization (ALS) has been used, where auxiliary lasers having different wavelength than that of the main laser sense the arms independently. However, it is not trivial to scale the system of Advanced LIGO due to its configuration. A new type of the ALS system was designed for KAGRA. The configuration of the new ALS system is simple and thus it is compatible with the interferometers of the third generation detectors. Along with a design study on the noise performance, an experimental test of the new ALS system in KAGRA was performed. In the experimental test, lock acquisition of the Fabry–Perot Michelson interferometer of KAGRA was achieved using the ALS system, which demonstrated the ALS system was ready for locking the full interferometer of KAGRA. The characterization of the ALS system was also performed; the residual fluctuations of the arm cavities were evaluated to be less than 5Hz in terms of root mean square, which is smaller than the linewidth of the arm cavity. Utilizing the results obtained in KAGRA, the performance of the ALS system in the third generation detector was simulated, along with discussions on necessary modifications to the KAGRA ALS system. The results indicated that lock acquisition of the third generation detector will be feasible by scaling the KAGRA ALS system. It was also pointed out that a new scheme with a sub-carrier field will make the lock acquisition process more reliable.

1. Introduction

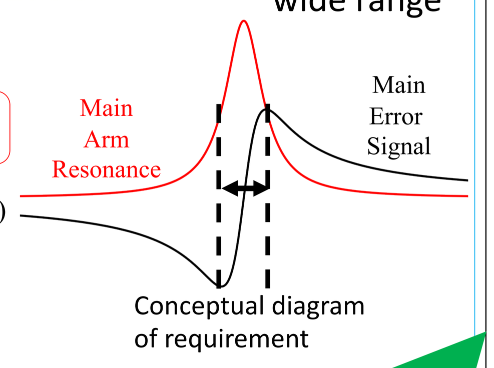
* Locking the interferometer is an essential part of a GW detector.
* Difficult!!! → - Non-linear error signals, - 5 DoFs are coupled

→ **- Wide linear range,**
- Resolved DoFs } *Required for lock acquisition*

* Solution: Arm Length Stabilization **(ALS)** — One Arm ↑ Follow & Sense => Arm DoFs resolved, wide range
→ Auxiliary green lasers sense arm cavities — One Laser
* Requirement: Arm DoFs must be controlled within the linear range of the main laser signal

Δf_{ARM} < (arm linewidth) = 33 Hz (KAGRA single arm)

(Δf_{CARM} < (CARM linewidth) = 1.6 Hz → lock acquisition of full IFO will be even more simplified.)



Conceptual diagram of requirement

* Even more challenging in the 3G detectors
∵ Longer arm → narrower linewidth

2. Design & Implementation

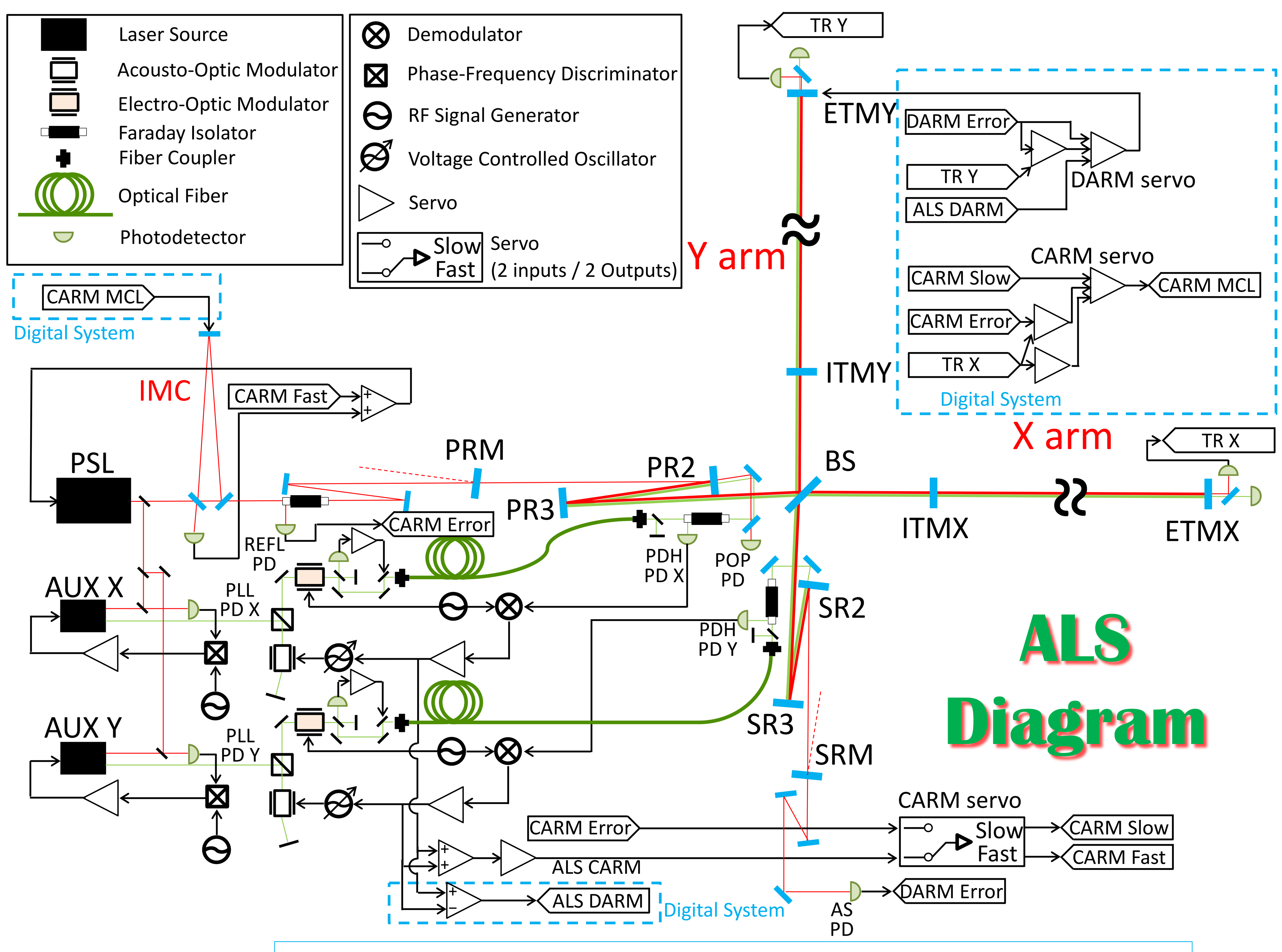
* We designed a new type of the ALS system (see the right)
c.f.) aLIGO ALS [Class. Quan. Grav., **31** 245010, (2014).]

*** Features of Our New Scheme: Simplified, thus scalable to 3G**

	KAGRA	Advanced LIGO
From where to inject green	Central area	End stations
Optical fibers	Within the central area	Along the arms
Signals of the arm DoFs	Summations in electronics	Optical beat notes
Number of optical sensors	4 (or 6[a])	6
Number of SHG setups	2	3

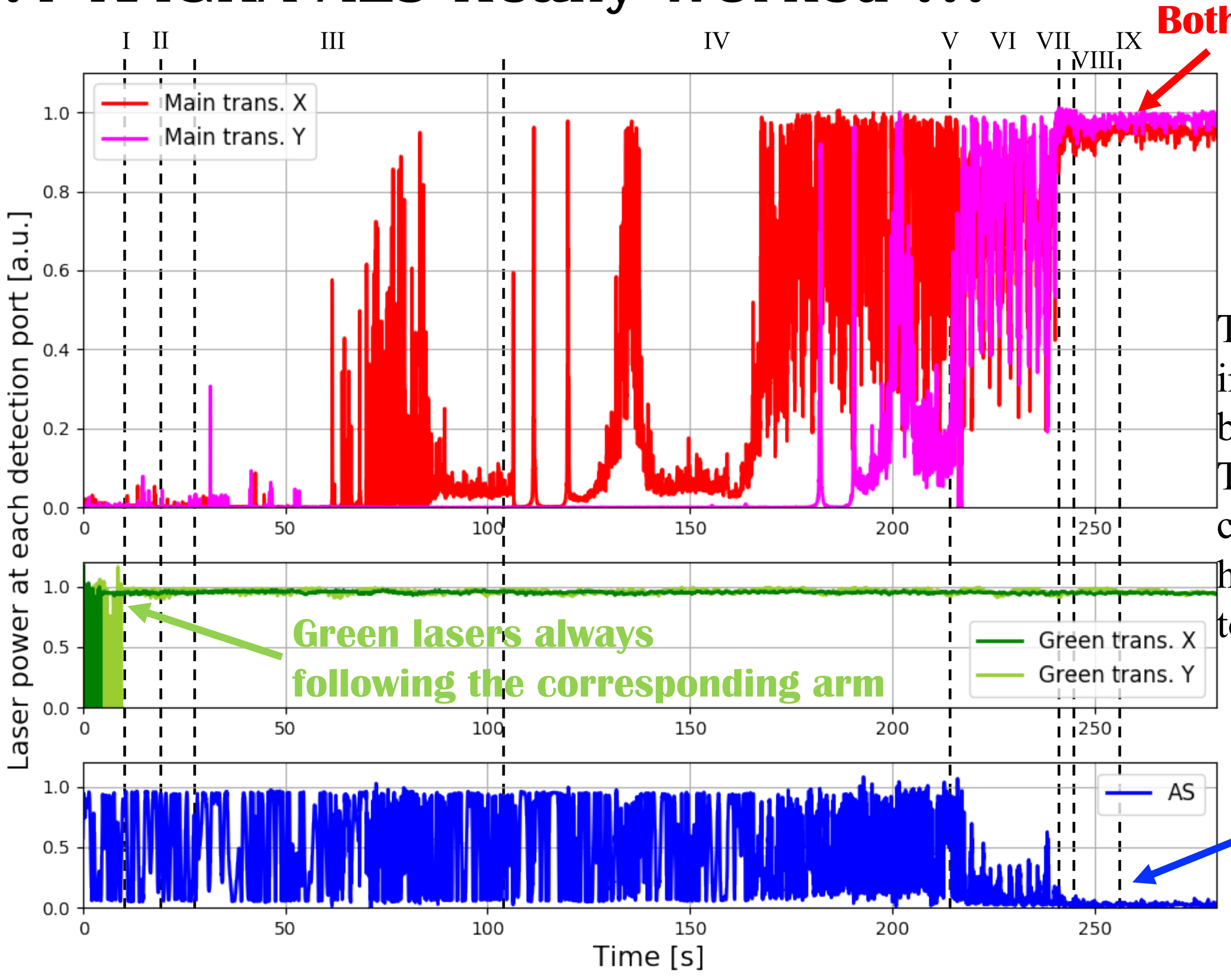
[a] If the fiber noise cancellation loops are involved.

* Implemented and tested in KAGRA Aug 2018 – Aug 2019
* Design study and first experimental results
→ *To be published in CQG*



3. Results: KAGRA ALS

3.1 KAGRA ALS Really Worked !!!



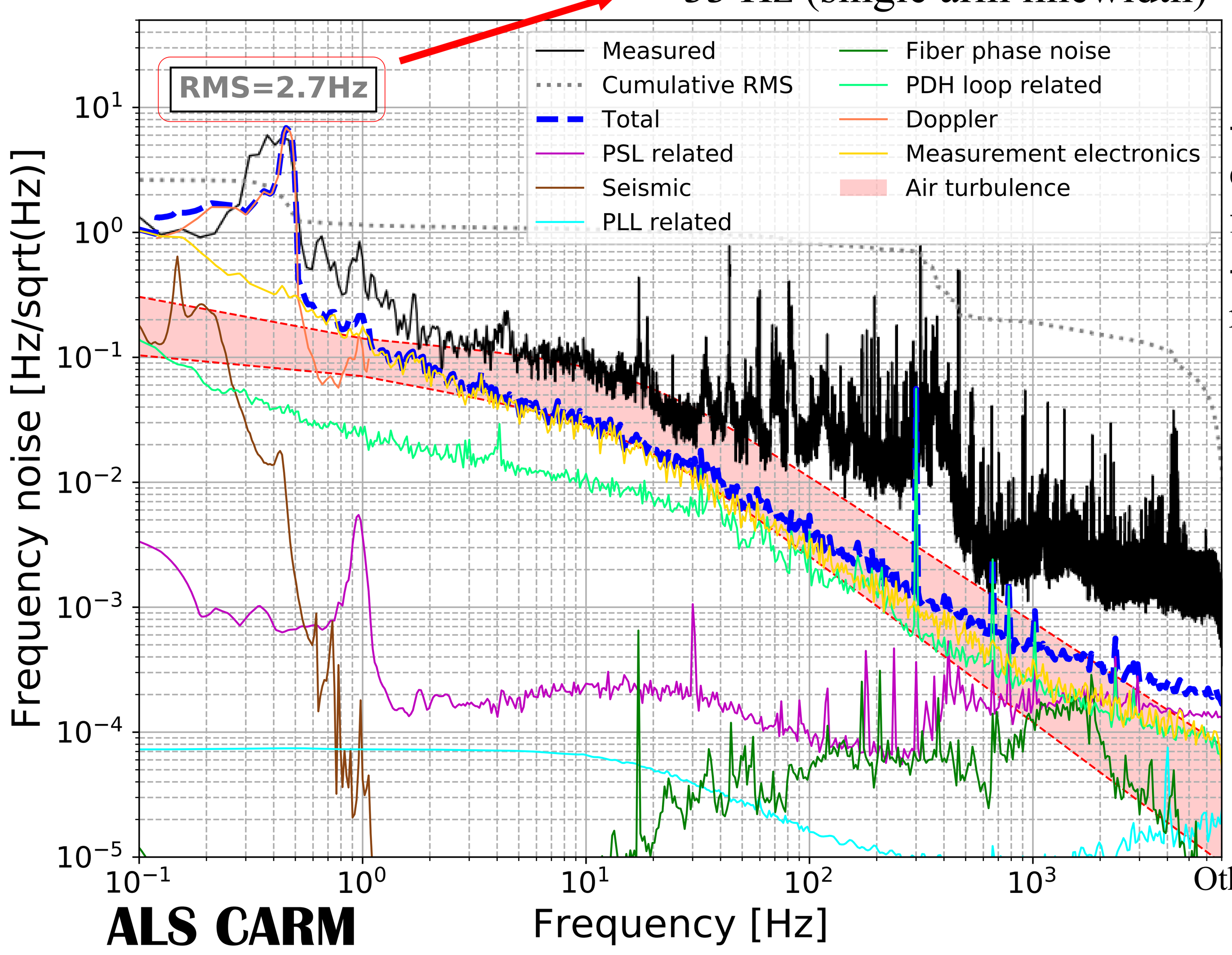
FPMI Lock Achieved!!!

The Fabry-Perot Michelson interferometer was locked by using the ALS system. The CARM and DARM controls were directly handed over from the ALS to the main laser PDHs.

Fig: Time series plot of how the optical power evolved as lock acquisition process proceeds.

3.2 Characterization

< 33 Hz (single arm linewidth) → **Requirement Satisfied!!!**



ALS CARM Noise Budget

- Fiber noise cancellation effectively suppressed the fiber noise contributions
- Noise budgeting work revealed that
  * Doppler noise from suspended mirrors
  * Air turbulence

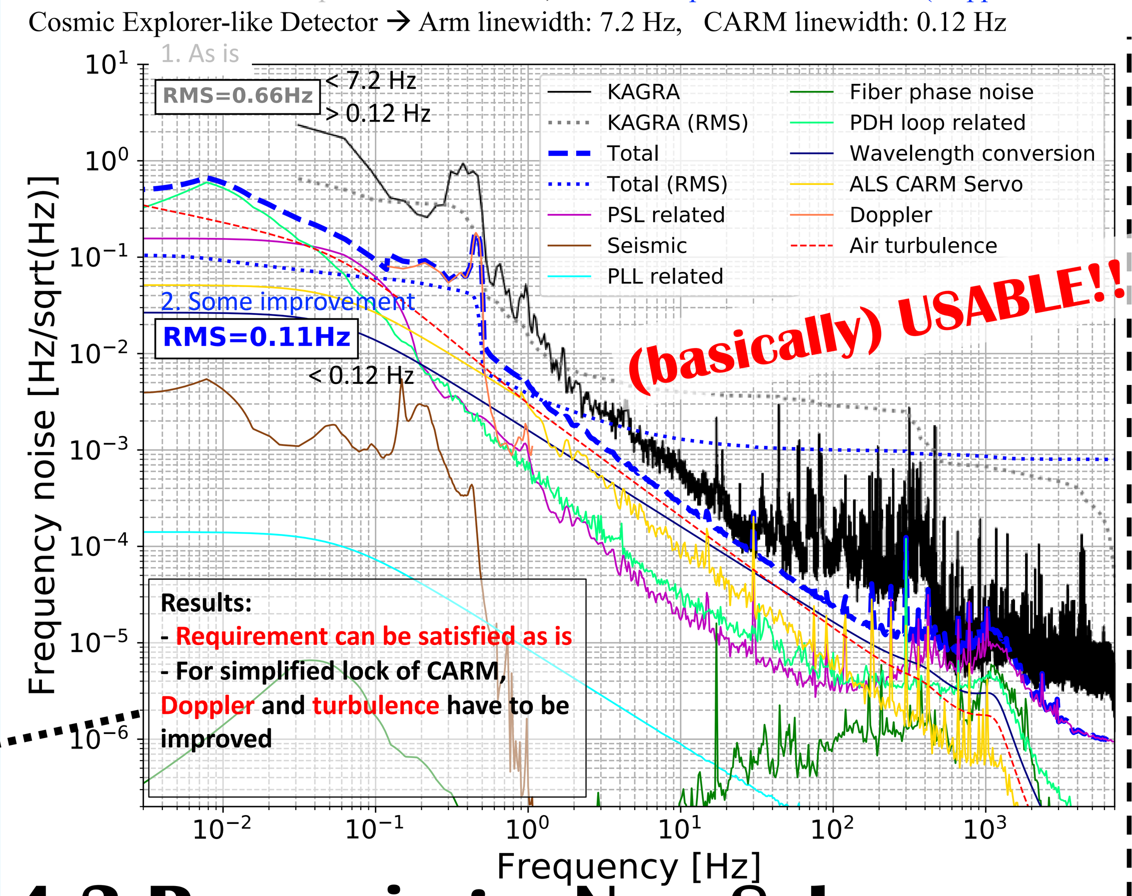
need to be reduced for more improving the overall performance

Other results: 4.4 Hz for X arm, 4.2 Hz for Y arm, 2.7 Hz for CARM, 2.8 Hz for DARM

4. Results: ALS in the 3G detectors

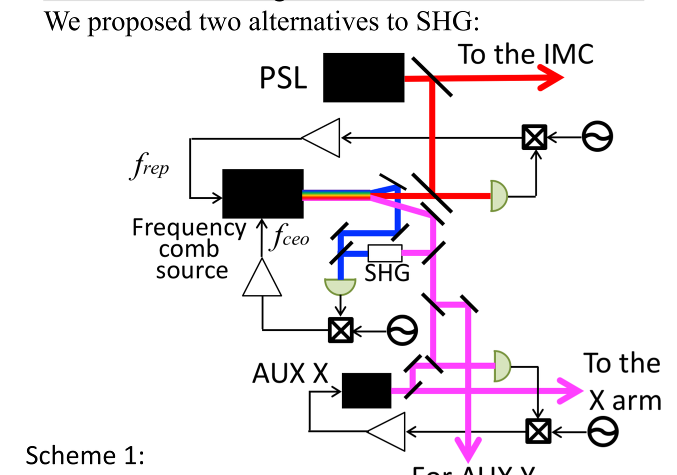
4.1 KAGRA-Type ALS Useful in 3G ?

Noise estimation of 3G ALS, where KAGRA-type ALS is assumed.
Two estimation: 1. No improvement assumed, 2. Some improvement assumed (Doppler and turbulence)
Cosmic Explorer-like Detector → Arm linewidth: 7.2 Hz, CARM linewidth: 0.12 Hz

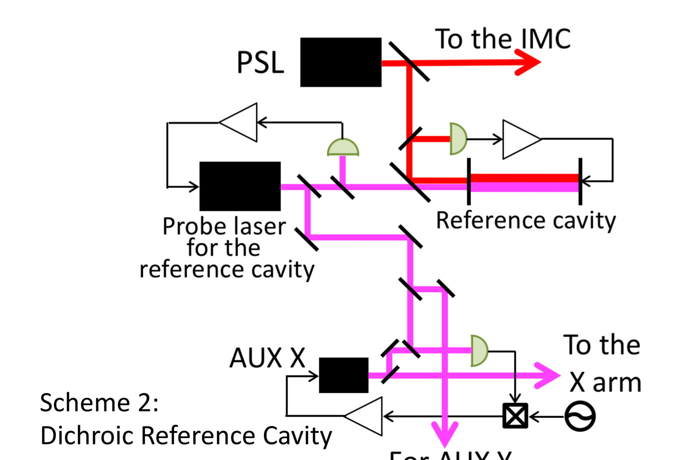


4.2 Wavelength Conversion

Silicon is black → "green lock" cannot be used as is.
We proposed two alternatives to SHG:

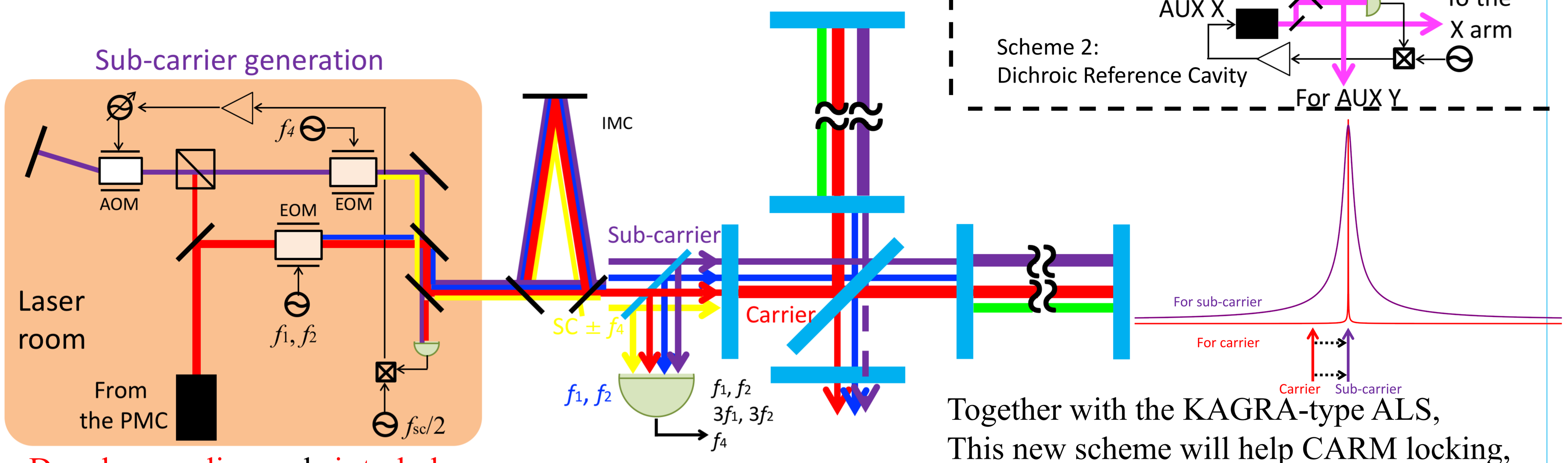


Scheme 1: Optical Frequency Comb



Scheme 2: Dichroic Reference Cavity

4.3 Proposing a New Scheme



Doppler coupling and air turbulence:
Consequence of different optical path btw the main and green lasers

Together with the KAGRA-type ALS, This new scheme will help CARM locking, even if the ALS CARM noise level does not improve.

Drastic Solution:
Common path ALS = Sub-carrier lock of CARM

Conclusion

- A new type of the ALS system was designed for KAGRA (Design scalable to 3G)
- Implemented in KAGRA → Achievement of FPMI lock demonstrated the performance
- Noise characterization showed that the system satisfied the requirement
- Performance of 3G ALS was simulated → KAGRA-type will satisfy the requirement
- Doppler and turbulence need to be mitigated for further improvement
→ A new scheme, sub-carrier CARM locking, will remove them