LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Fabrication Acceptance Review

Status of Input Optics EOM Testing, Modeling and Discussion of need for Waivers from Systems

Input Optics Group and LIGO Lab Staff

Distribution of this document:
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1. Introduction

This document has been assembled to allow the completion of the IO Fabrication Acceptance Review (FAR). During the FAR questions were raised by the review committee related to whether or not the EOM meets requirements. There has been some confusion on the part of the IO team resulting from subsequent discussions with other subsystems about just what the requirements are. For the purpose of the FAR we will assume that the requirements described in the "Input Optics Subsystem Design Requirements Document" T020020-04-D are the operative requirements. The responses below describing testing and modeling of the EOM performance and/or requests for waivers from Systems will be with respect to these requirements.

2. Modulation Depths

Requirement

The modulation depth Requirement is described in T020020-04-D, section *3.3.2 Modulation Depths* and says

"Modulation depths depends on the final length and alignment sensing and control scheme. Based on the conceptual design, the following range is sufficient:

- The IO must provide for modulation depths in the range m = 0-0.8."

IO Team Response

It is our understanding that this requirement was revised in the IO Procurement Readiness review (T080075-01-D). Section **4.5 Modulation depth** states:

"4x4x40mm RTP crystals were used to build the eLIGO modulators, using multiple electrodes on one crystal to reduce the number of crystal interfaces. Using those modulators, a modulation depth of 0.4 with a drive power of 24dBm was observed with an electrode length of 22 mm.

Using the full 40 mm electrode length will allow the required 0.8 modulation depth, should it be needed for the MZ modulation scheme."

The MZ modulation scheme is not installed which reduces the required modulation depth to 0.4. Note that a modulation index of 0.8 in the MZ scheme referred to the one arm modulation index. This is equivalent to a modulation index of 0.4 in the installed serial modulation case (this assumes a linearized Bessel function J1(m) ~ m).

This is also consistent with the at that time prevailing (and also the current) ISC design for length and alignment sensing which states in T070247-01:
"The design of the modulation and readout scheme is the responsibility of the ISC. The modulation is implemented by Input Optics (IO), according to the requirements of the ISC."

and
"We intend to use serial modulation in one crystal, i.e. we do not need a Mach-Zehnder interferometer (see appendix B). However a Mach-Zehnder could be retrofitted."

Table 14 mentions the used modulation index of 0.2 for both frequencies. See also the Gamma's on Table 6 and 9.

The currently installed electrodes of 15mm for each of the main modulation frequencies were approved and would indicate a requested modulation index around 0.26 as a requirement for each of the two main modulation frequencies. However, should the need arise,we can replace the current electrical circuit with a circuit with longer electrodes for one of the frequencies at the expense of the other frequencies. Otherwise, we will have to go back to a multi-modulator design.

In document E1300758 modulation depth measurements were discussed in *Subsection 5.1 Modulation Depth LHO* and *Subsection 5.3 Modulation Depth LLO*.
The modulation indices at LHO were measured to be 0.39 and 0.31 for the two main frequencies, sufficient to meet the expected index of 0.26. A later measurement in December 2014 (See wa-alog-15661) showed modulation indices of 0.284 for a 21.5dBm drive (2.5dB below the nominal drive) at 45MHz and 0.205 for a 17.27dBm drive at 9.1MHz.
The modulation indices at LLO were measured to be 0.609 and 0.295 for the two main frequencies in October 2014 (See la-alog-15108)

Based on our understanding of the requirements, this is sufficient. However, if the project requires a larger modulation index, we request a waiver for this requirement.

3. Modulation amplitude noise

Requirement

The amplitude noise requirement is described in T020020-04-D, section *3.3.3 Modulation Amplitude Noise Requirements* and says

"Fluctuations in the amplitude of the modulation sidebands introduce noise in the servo system and also change the intensity of the carrier which then changes for example the radiation pressure noise in the arm cavities. We require:

- · RAN SB (f) $< 10^{-7}\text{Hz}^{-1/2}$ $f < 10$ Hz
- · RAN SB (f) $< 10^{-7}\text{Hz}^{-1/2}(10\text{Hz}/f)$ 10 Hz $< f <$ 100Hz
- · RAN SB (f) $< 10^{-8}\text{Hz}^{-1/2}(100\text{Hz}/f)^{1/2}$ 100 Hz $< f <$ 1 kHz
- · RAN SB (f) $< 3\times10^{-9}\text{Hz}^{-1/2}$ $f >$ 1 kHz"

IO Team Response

We request a waiver for this because this is impossible to measure without the main interferometer working at or near design sensitivity and being limited by technical radiation pressure noise. We flagged this early in the design phase as one of the issues we will not be able to verify because of the challenges to measure it.

4. Modulation Phase Noise

Requirement

The amplitude noise requirement is described in T020020-04-D, section *3.3.4 Modulation Phase Noise Requirements* and says

“Fluctuations in the modulation frequency due to oscillator phase noise beat at the length sensing port photodetectors and produce technical noise.

- $\Phi_{OSC} < 10^{-5}$ rad/Hz$^{1/2}$ (10 Hz/f)$^{3/2}$ 10 Hz < f < 100Hz
- $\Phi_{OSC} < (3x10^{-5})$ rad/Hz$^{1/2}$ (100 Hz/f) 100 Hz < f < 1 kHz
- $\Phi_{OSC} < (3x10^{-5})$ rad/Hz$^{1/2}$ f > 1 kHz

IO Team Response

The oscillator is provided by CDS and is not part of IO.

5. Modulation Cross Products

Requirement

The requirement for the amplitude noise is described in T020020-04-D, section *3.3.5 Modulation Cross Products* and says

“ There are three modulation frequencies in use (including the modulation for the mode cleaner. The modulation process produces intermodulation products (sidebands on sidebands). These intermodulation products can mix down into the GW band and produce technical noise. These modulation cross products look like fluctuations in the modulation frequency and have identical requirements:

- $\Phi_{OSC} < 10^{-5}$ rad/Hz$^{1/2}$ (10 Hz/f)$_{3/2}$ 10 Hz < f < 100Hz
- $\Phi_{OSC} < (3x10^{-7})$ rad/Hz$^{1/2}$ (100 Hz/f) 100 Hz < f < 1 kHz
- $\Phi_{OSC} < (3x10^{-8})$ rad/Hz$^{1/2}$ f > 1 kHz”

IO Team Response

Please provide any information on ex situ or in situ testing or modeling that was done to estimate the IO EOMs Modulation Cross Products and if necessary discuss the need for a waiver.

6. RFAM

Requirement

There is not a requirement in T0200020-04-D for RFAM.

IO Team Response

Specifications were set on the wedge of the EOM front an back faces to reduce RFAM which is discussed in document E1300758 in *Section 3 Design subsection Reduced RFAM*. In addition, RFAM measurements are discussed in *Section 5.2 RFAM Modulation Depth LHO* and *Section 5.4 RFAM Modulation Depth LLO*.

RFAM was measured at LHO in Dec 2014 - wa-alog-15661, both again in the PSL, and in transmission of IMC. At LLO, RFAM was measured in April 2012 (la-alog-3034). EOM resonances were measured most recently on 13 October 2014 (la-alog-15108).