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LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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LIGO Caltech 40-Meter PSL Supplemental Report

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1 Introduction

This is a supplemental document for *LIGO Caltech 40-Meter PSL Commissioning Report*, LIGO–T010145–00–D which shows the performance of the pre-stabilized laser (PSL) in the 40-meter interferometer (40m).

In the beginning of 2002, the old 1 watt master oscillator inside the *MOPA 126* reached the end of its life and was exchanged for a 700mW master oscillator which should last longer. This document provides some supplemental measurements for the performance of PSL, focusing on the intensity noise, the frequency noise of the pre-mode cleaner (PMC), and the frequency noise of the frequency stabilization servo (FSS). These will be a reference for the mode cleaner (MC) and interferometer (IFO).

2 Applicable Documents

2.1 LIGO Documents

2.1.0.1 PSL

- *Prestabilized Laser Design Requirements*, **LIGO–T950030–03–D**
- *(Infrared) Pre-stabilized Laser (PSL) Design Requirements*, **LIGO–T970080–09–D**
- *(Infrared) Pre-stabilized Laser (PSL) Conceptual Design*, **LIGO–T970087–04–D**
- *IR PSL Conceptual Design Document*, **LIGO–T970114–00–C**
- *(Infrared) Pre-stabilized Laser (PSL) Electronics Design Requirements*, **LIGO–T970115–00–C**
- *(Infrared) Pre-stabilized Laser (PSL) Final Design Document*, **LIGO–T990025–00–D**
- *LIGO Hanford Observatory 2k IFO PSL Test Report*, **LIGO–T000031–00–D**
- *LIGO Caltech 40-Meter PSL Commissioning Report*, **LIGO–T010145–00–D**
- *IO Position and Angle Sensing System, 40m IFO*, **LIGO–T020119–00–D**
- *Measurement of the laser beam profile at the 40 Meter Prototype Interferometer*, **LIGO–T020143–00–R**

2.1.0.2 Circuit diagrams

- *Pre Mode Cleaner Servo Card*, **LIGO–D980352–E–C**
- *Frequency Stabilization Servo*, **D980536–F–C**
- *PSL Block Diagram*, **LIGO–D000214–00–C**

2.2 Non-LIGO Documents

- *126 MOPA Performance Data*
- *Test Report 126 MOPA*

The above two non-LIGO documents are delivered with each 10-W laser.

3 Optical Configuration

3.1 Servo Functionality

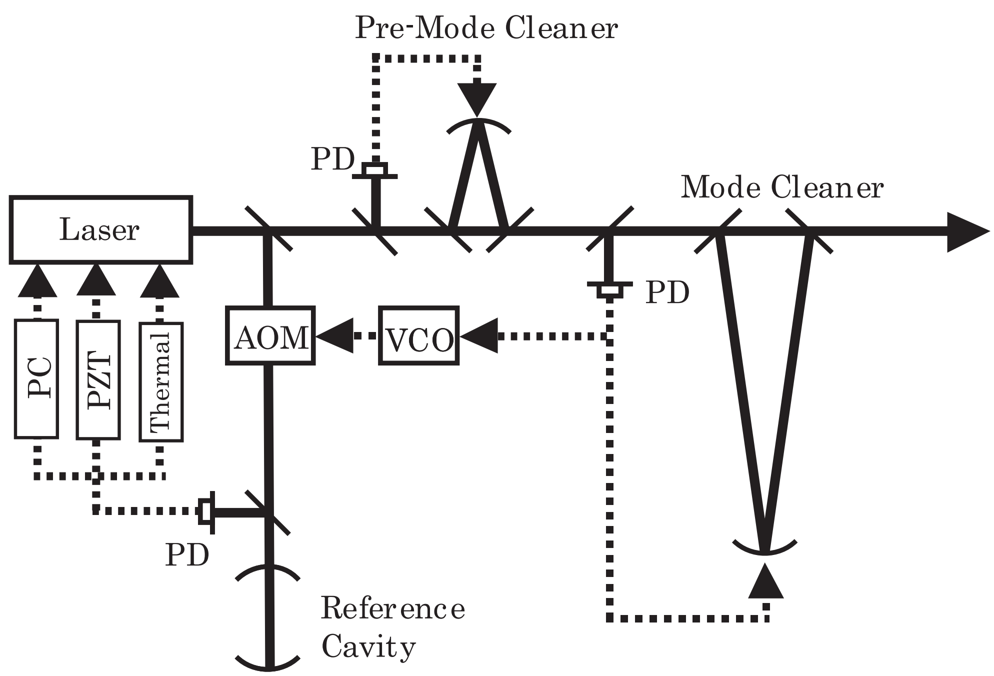

Figure 1: Conceptual block diagram of PSL controls

Figure 1 shows a simple schematic diagram of the PSL controls including the MC control. The PSL consists of two control loops. The laser frequency is stabilized by the FSS, and the spatial mode of the laser is stabilized by the PMC.

In the FSS, the modulation is supplied by a 21.5 MHz tuned Pockels cell in the low-power beam path (see Figure 2). The control signal is fed back to both a phase-correcting Pockels cell inside the MOPA and a fast PZT actuator on the master oscillator. The specification of the cross over frequency is around 12 kHz. There is also a slow thermal compensating actuator controlled by the VME processor. It works when the feed back signal of the fast PZT loop has a certain DC offset.

The PMC modulation is supplied by another 35.5 MHz tuned Pockels cell, and the control signal is fed back to a PZT on the end mirror of the PMC to control the cavity length. See *PSL Block Diagram*, LIGO D000214–00–C for details.

Light coming from the PSL enters the 13 m MC. The frequency and spatial mode of the laser is also stabilized by the MC for the main 40 m IFO. Low frequency control signals are fed back to one of the suspended mirror of MC and high frequency control signals are fed back to laser frequency through the voltage oscillator modulator (VCO) which is placed before the reference cavity (RC) and makes a 75MHz frequency shift on the acousto-optic modulator (AOM). In this document, the MC is used as a monitor for the frequency noise of PSL.

3.2 Table Layout

Figure 2 shows a table layout of the PSL. The present table layout was proposed in the last commissioning report of LIGO-T010145-00-D. Optical layout of the RC and upstream of PMC is the same as before. Several optics have been added downstream of PMC.

Three Pockels cells have been added. The first Pockels cell produces 29MHz sidebands to lock the MC, and the second and third Pockels cells produce 33MHz and 166MHz sidebands for IFO. Periscope, angle/position sensors and optical spectrum analyzer are added in the end of PSL table, and transmitted port of the MC is also added on this table.

4 Free-running Intensity Noise

Figure 3 shows the measured free-running relative intensity noise of the PSL. A Thorlab PD55 is used for these measurements. The flat area above 20kHz is limited by the detector noise of PD55 which depends on the incident power at the photo detector.

Measured free-running relative intensity noise of the 10-W LIGO Laser for 40 m is drawn as a green curve and meets the Lightwave Electronics target specification drawn as a thick gray line. Measured free running intensity noise of the PMC transmitted light and the MC transmitted light are drawn as a blue and a red curve. The PMC transmitted light is contaminated by acoustic noise producing length fluctuation on the PMC from 200Hz to 3kHz. This acoustic noise contributes to the frequency noise of PSL and it will be shown in the next section.

Length and alignment fluctuation of the MC cavity by mechanical resonances of the suspensions produce additional intensity noise at the low frequency of MC transmitted light. Note that the height of the peak of 1Hz is not correct. It is not determined by only the intensity noise around 1 Hz but also the relationship between the aperture of the photo diode and the beam size at the photo detector. Since beam orientation is fluctuating too much around 1 Hz compared with the aperture of the photodiode, there is a coupling from beam jitter to the intensity noise. A photo detector with large enough aperture compared with beam diameter is necessary for more precise measurement.

We have found that the acoustic noise of the HEPA filter above the PSL enclosure increases the intensity noise in all frequencies. Fig. 4 shows the measured data of the PSL free-running relative intensity noise with the HEPA filter on. We know that the HEPA filter also increases the frequency noise of PSL as shown in the next section. We can stop the HEPA filter for the noise performance, but the HEPA filter is needed for clean environment of long term operation, so this problem need to be addressed.

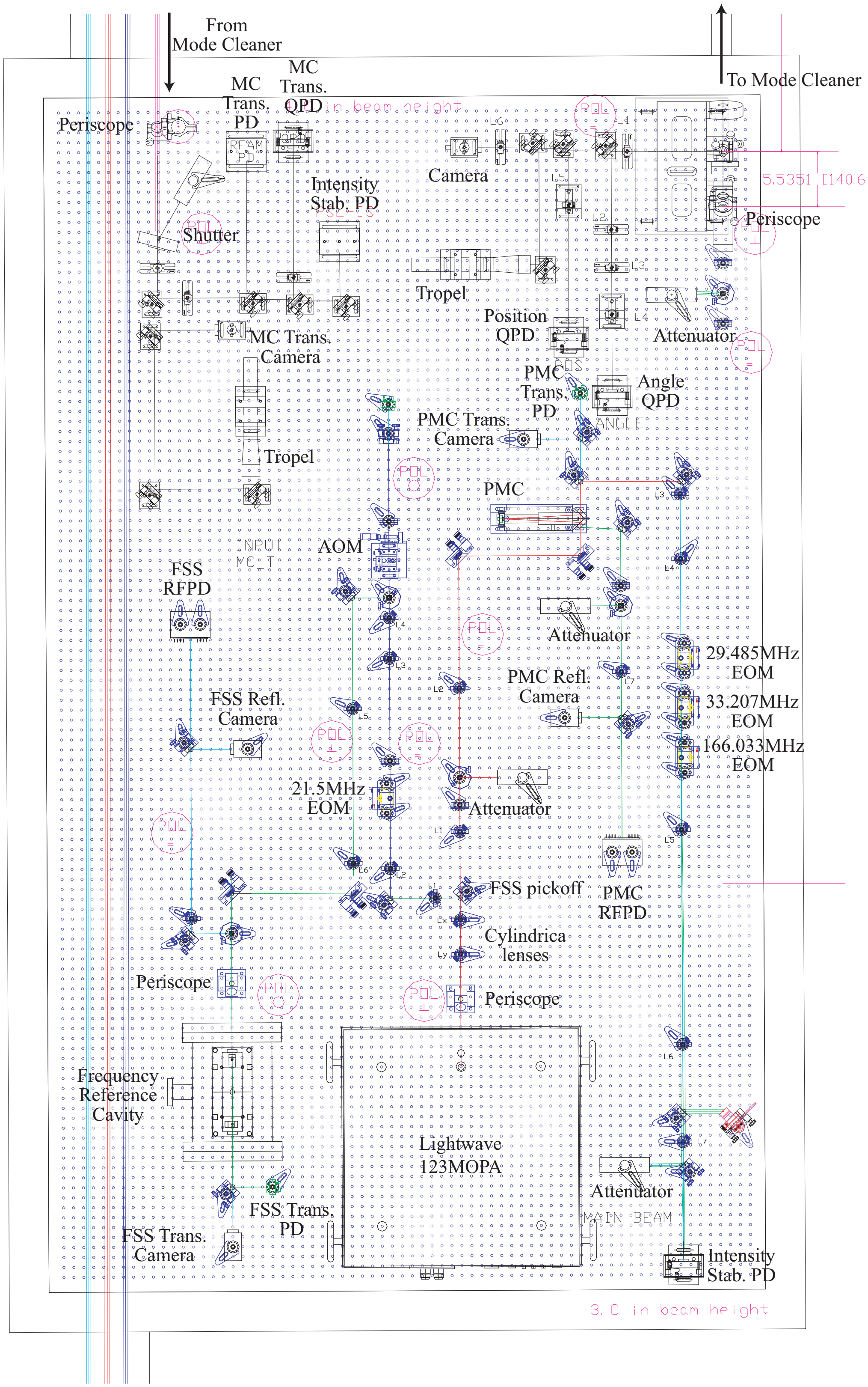

Figure 2: Layout of 40-meter PSL optical table

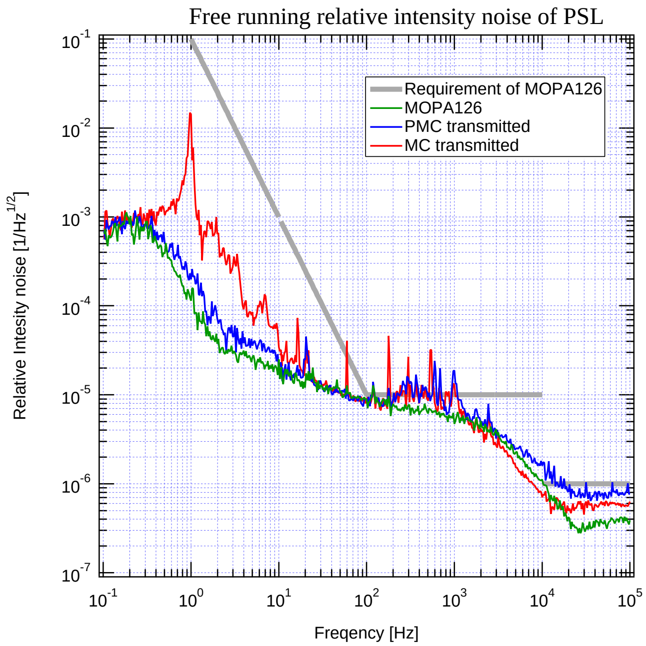

Figure 3: Measured free-running intensity noise of the PSL.

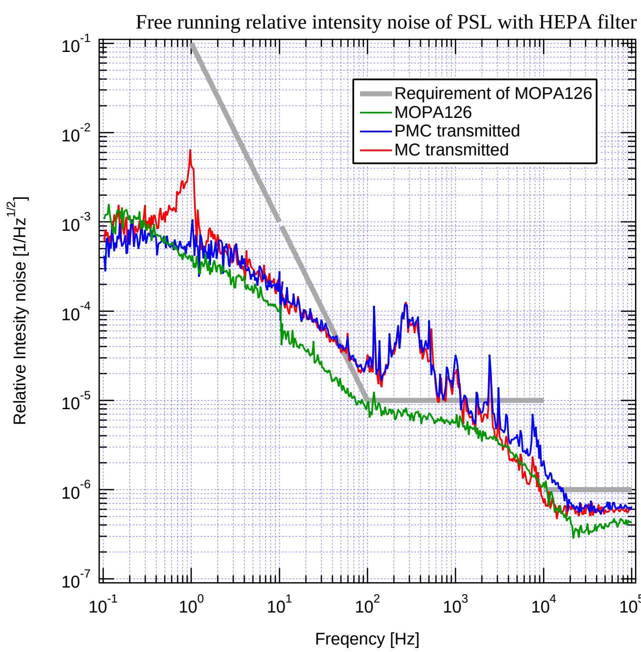

Figure 4: Measured free-running intensity noise of the PSL with the HEPA filter above the PSL enclosure turned on.

5 Frequency Stabilization Servo (FSS) Performance

5.1 Free-running Frequency Noise

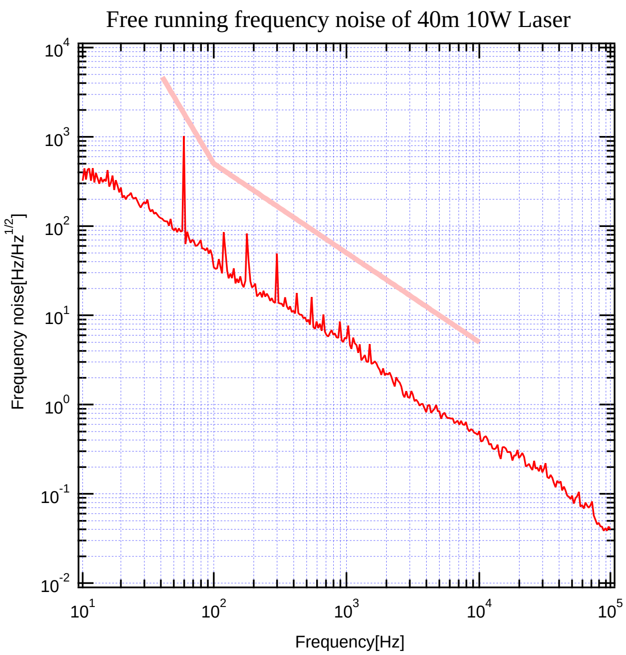

Figure 5: Measured free-running frequency noise of the LIGO 10-W Laser for 40m.

Figure 5 shows a measured free-running frequency noise of the 40-meter 10-W Laser. The measurement was performed with a loose-locked RC. The reason for using a loose-locked cavity is that the noise of a tight locked cavity would be dominated by other electrical noise. The noise of the cavity has to be dominated by the frequency noise in all measured frequencies for the evaluation of free-running frequency noise.

Free-running noise of laser $N_{\rm free}$ is suppressed by the open-loop gain of FSS $G_{\rm FSS}$, and this suppressed in-loop noise of FSS $N_{\rm cl}$ is described as

$$N_{\rm cl} = \frac{1}{1+G_{\rm FSS}} N_{\rm free}. \tag{1}$$

The free-running noise can be calculated by the measurement of the loose-locked open-loop gain of FSS and the loose-locked in-loop noise of FSS. The method of measurement for the in-loop noise and the open-loop gain is explained in the next paragraph.

Thick line in the graph is the target specification provided by the Lightwave Electronics. Measured free-running frequency noise of the 40-meter 10-W laser meets the specification.

5.2 Servo Transfer Function

IR PSL CDS Conceptual Design Document, LIGO-T970114-00-D lists the design requirements for the FSS and PMC servos, including the unity gain frequencies and in-loop frequency noise limits.

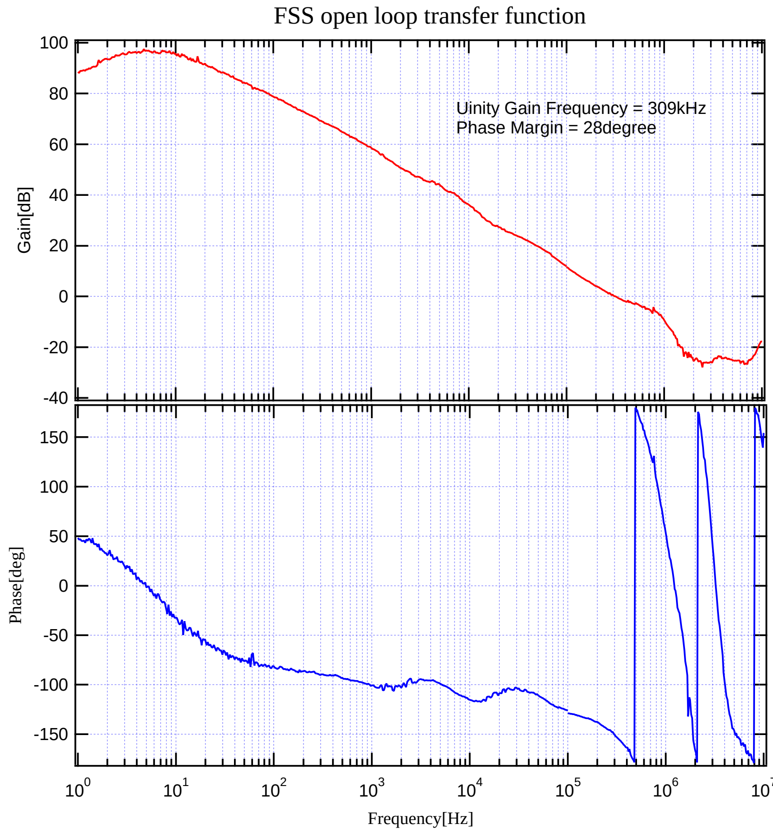

Figure 6: Measured transfer function of FSS servo loop

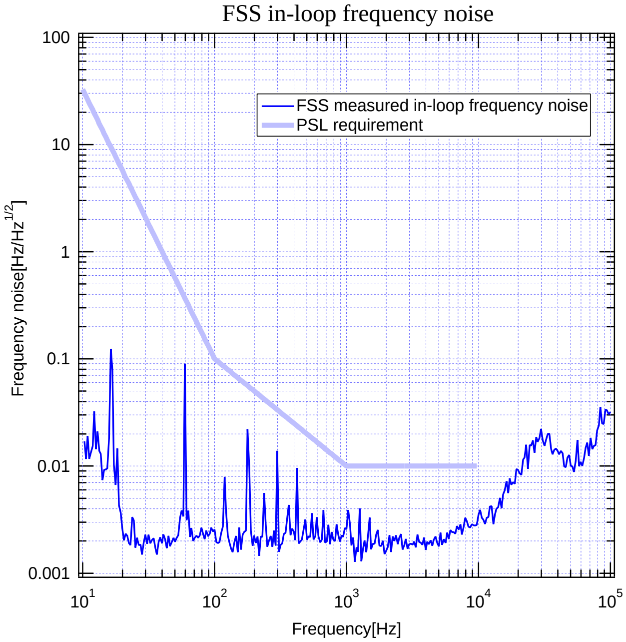

Figure 7: Measured FSS in-loop frequency noise versus design requirement

The requirement for the unity gain frequency of the FSS transfer function is 500-800 kHz.

The transfer function of FSS $G_{\rm FSS}$ is measured by sending a sine wave of the spectrum analyzer from 'Test in 2' to 'Mixer out' on the FSS servo board and sweeping from 1 Hz to 10 MHz while the servo is locked. Low frequency transfer function from 1 Hz to 100 kHz is measured by HP3562A and high frequency transfer function from 100 kHz to 10 MHz is measured by HP4195A.

Transfer function from 'Test in 2' to 'Mixer out' with the FSS servo on is the closed-loop transfer function $C_{\rm FSS}$ and it is related to the open loop transfer function $G_{\rm FSS}$ as follows,

$$C_{\rm FSS} = \frac{1}{1 + G_{\rm FSS}}, \tag{2}$$

In the practical measurement, the transfer function from 'Test in 2' to 'Mixer out' with the FSS servo is not precisely the closed-loop transfer function. The measured transfer function actually becomes

$$\frac{H_{\rm sum}}{1 + G_{\rm FSS}}, \tag{3}$$

where $H_{\rm sum}$ is the gain from 'Test in 2' to 'Mixer out' without the FSS servo. Generally, $H_{\rm sum}$ is not unity, so it should be measured independently when the FSS is not locked, and the Eq. 3 is divided by the measured $H_{\rm sum}$. The open loop transfer function is calculated by these two measurements.

Figure 6 shows measured transfer function. This graph shows the unity gain frequency of 309 kHz with the FSS common gain slider at +26 dB and the FSS fast gain slider at +13 dB. This unity gain frequency does not meet the requirement because the phase delay around the unity gain frequency is too much. This will cause a phase delay for the MC servo and a limitation of unity gain frequency of the MC servo in the future.

5.3 In-loop Frequency Noise

The design requirement for the FSS in-loop frequency noise is listed in *IR PSL CDS Conceptual Design Document*, LIGO-T970114-00-D. This limit is shown by the solid black curve in Fig. 7 with the measured noise.

This frequency noise is estimated by the error signal of the FSS. The calibration factor from V to Hz is estimated by the peak to peak voltage of the error signal of FSS around the resonance when the loop of FSS is open. If the slope around resonance were extended to the position of the peaks, the height of this slope will be twice the height of the peak to peak voltage, and the width between peak positions corresponds to the full width half maximum (FWHM) of the RC. The ratio of this height and the FWHM gives the calibration factor from V to Hz. In this measurement, the calibration factor is 37.16 kHz/V.

The graph shows that the FSS looks to meet the design requirement. However this measurement does not show the real frequency noise of the PSL, just the frequency noise of the RC. This is because the error signal of the FSS does not include length fluctuation of RC. If the gain of FSS were infinity, the frequency fluctuation of laser would follow the fluctuation of reference cavity length. To estimate the real frequency noise of PSL, another cavity which has the same or better sensitivity than the existing RC is needed. The estimation of real frequency noise of PSL using the MC is shown in the section 7.

6 Pre-Mode Cleaner Servo (PMC) Performance

6.1 Servo Transfer Function

The transfer function of PMC $G_{\rm PMC}$ is measured by sending a sine wave of the spectrum analyzer HP3562A from 'FP2 TEST' to 'MIXER OUT' on the PMC servo board and sweeping from 1 Hz to 100 kHz while the servo is locked. The transfer function from 'FP2 TEST' to 'MIXER OUT' [1] is the closed-loop transfer function $C_{\rm PMC}$ and it is related to the open loop transfer function $G_{\rm PMC}$ as follows,

$$C_{\rm PMC} = \frac{1}{1 + G_{\rm PMC}}, \tag{4}$$

Result are shown in Fig. 8. The design requirement for the unity gain frequency of PMC transfer function is no less than 600 Hz. The measured unity gain frequency is 7.6 kHz, well above the design requirement. The effect of two notch filters can be seen around 37 kHz and 71 kHz.

6.2 Out-loop Frequency Noise

Figure 9 shows the measured PMC frequency noise with the requirement. The frequency noise of PMC $N_{\rm PMC}$ is suppressed by the open-loop gain of PMC $G_{\rm PMC}$, so the in-loop frequency noise of PMC $N_{\rm PMCcl}$ is described as

$$N_{\rm PMCcl} = \frac{1}{1 + G_{\rm PMC}} N_{\rm PMC}. \tag{5}$$

The out-loop frequency noise of PMC can be calculated by the measurement of the in-loop frequency noise of PMC and the open-loop gain of PMC.

Noise of the PMC meets the requirement in all frequencies except for one peak. Above 10 kHz, the noise is limited by detector noise.

7 PSL frequency noise measured by MC

Real frequency noise of the PSL can be measured by another cavity which has the same or better frequency noise performance than the PSL. Since the MC is expected to have better frequency noise performance at high frequency, we tried to measure the real frequency noise of PSL using the MC. The result is shown in Fig 10.

Upper red curve is the PSL frequency noise measured by the MC, and lower blue curve is the frequency noise of the RC which is the same as Figure 7. The frequency noise measured by the MC has excess noise added by the MC length fluctuation: seismic noise, from 10 to 50 Hz, sensor noise of suspension from 30 to 300 Hz, acoustic noise from 300 to 3000 Hz; and electronic noise above 4 kHz. The real frequency noise of the PSL is expected to be between these two curves.

[1] Practical measurement has some gain from 'FP2 TEST' to 'MIXER OUT' while the servo is not locked, and it should be canceled out. This is the same as the case of FSS.

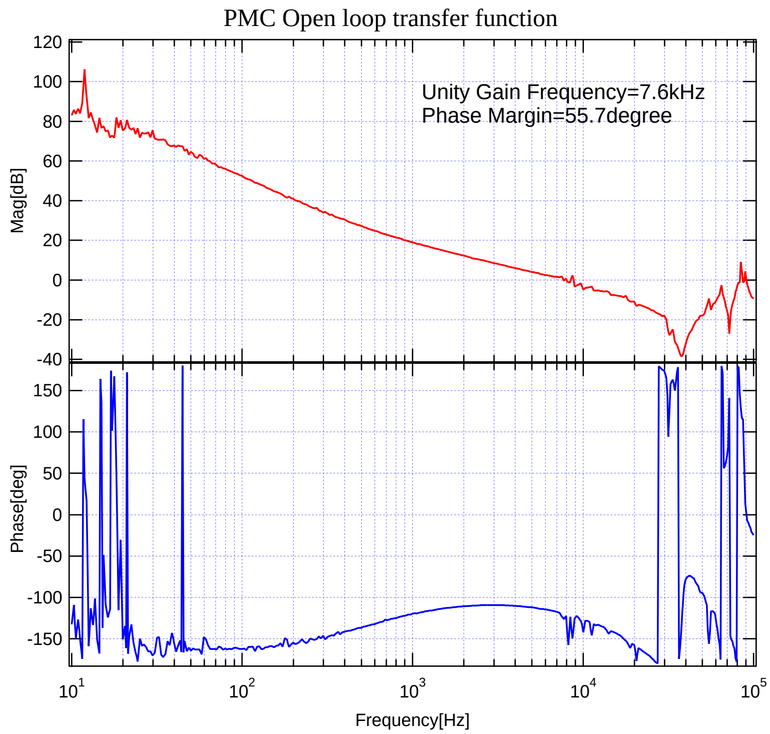

Figure 8: Measured transfer function of PMC servo loop

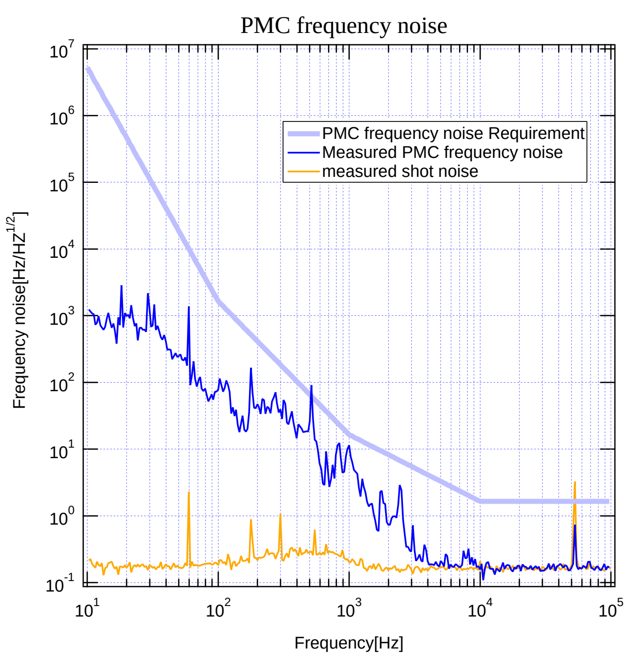

Figure 9: Measured in-loop frequency noise of PMC servo versus design requirement

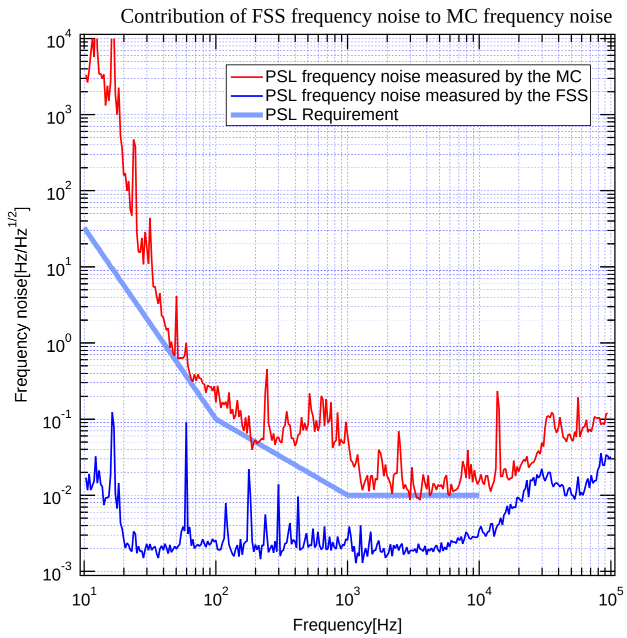

Figure 10: PSL frequency noise measured by MC

8 Summary

The 40 m PSL is locking robustly with a new master oscillator and the free running intensity noise, the in-loop frequency noise of the FSS and the out-loop frequency noise of PMC have been measured. The frequency noise of the FSS and PMC meet the design requirements and the total PSL frequency noise has been also measured by the MC. The difference between the PSL frequency noise measured by the FSS and by the MC exists because the MC adds excess frequency noise. Further identification of sources of total PSL frequency noise will be performed and this will be useful information for the 40-meter interferometer in the future.