LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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eLIGO Hanford Output Mode Cleaner Repair

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1 Introduction

On Sept. 8, Nic noticed that the Hanford OMC transmission was ≈ 25% lower than previously measured for both single bounce and full interferometer configurations [1]. Dani correlated the power drop with a power outage at Hanford, and Keita finally connected this with a decrease in the OMC Finesse from the original $\mathcal{F} = 367$ to $\mathcal{F} = 297$ [2]. In its faulty condition, the OMC transmits only 66% of the light, a critical problem for the squeezing experiments which limits the squeezing to 1dB [3].

After Sheon measured the LLO OMC to have a Finesse of 369.8 [5], the squeezer team replaced the LHO OMC with the LLO OMC [4]. In this note, we describe the measurements and methods to restore the LHO OMC to its former greatness.

References

[1] N. Smith, *OMC transmission is low again;* Sept. 8, 2010 LHO iLOG

[2] K. Kawabe, *OMC finesse and transmission;* Aug. 5, 2011 LHO iLog

[3] L. Barsotti, *Too many losses: data with H1 OMC;* Oct. 26, 2011 LHO iLog

[4] N. Smith, *OMC resonates;* Oct. 25, 2011 LHO iLog

[5] S. Chua, *L1 OMC inspection and resonance scan;* Oct. 21, 2011 LHO iLog

[6] S. Waldman, *The Enhanced LIGO Output Mode Cleaners* T080144

2 Methods

We need two sets of numbers to diagnose the OMC. First, we require the OMC transmission and mode matching. Second, we need the OMC finesse. The transmission measurements are performed with the laser locked to the OMC, while the Finesse measurements are done by sweeping the cavity via two techniques.

2.1 Locking to the OMC

The laser is locked to the OMC using a standard Pound-Drever-Hall lock controlling the “Fast” input of a lightwave 126 NPRO. The modulation is generated by a New Focus resonant EOM, driven by a MiniCircuits RF amplifier. The oscillator is an IFR running at 21.5 MHz and +3 dBm. The OMC reflected signal is measured with a Thorlabs PDA10CS, demodulated in a mixer, phased using cable, and low pass filtered with a MiniCircuits BLP-5. The low passed signal is further low passed by an Stanford Research Systems SR560 with 1 MHz low pass, before a New Focus LB1005 Servo controller makes a ±10 V control signal. To achieve sufficient dynamic range, the controller output is amplified by a Thorlabs piezo controller after being summed with a 9 V battery and piped through a 10 kOhm resistor.

The resistor, in combination with the 10 kOhm input impedance of the Thorlabs, matches the ±10 V controller output to the 0-10 V Thorlabs input.

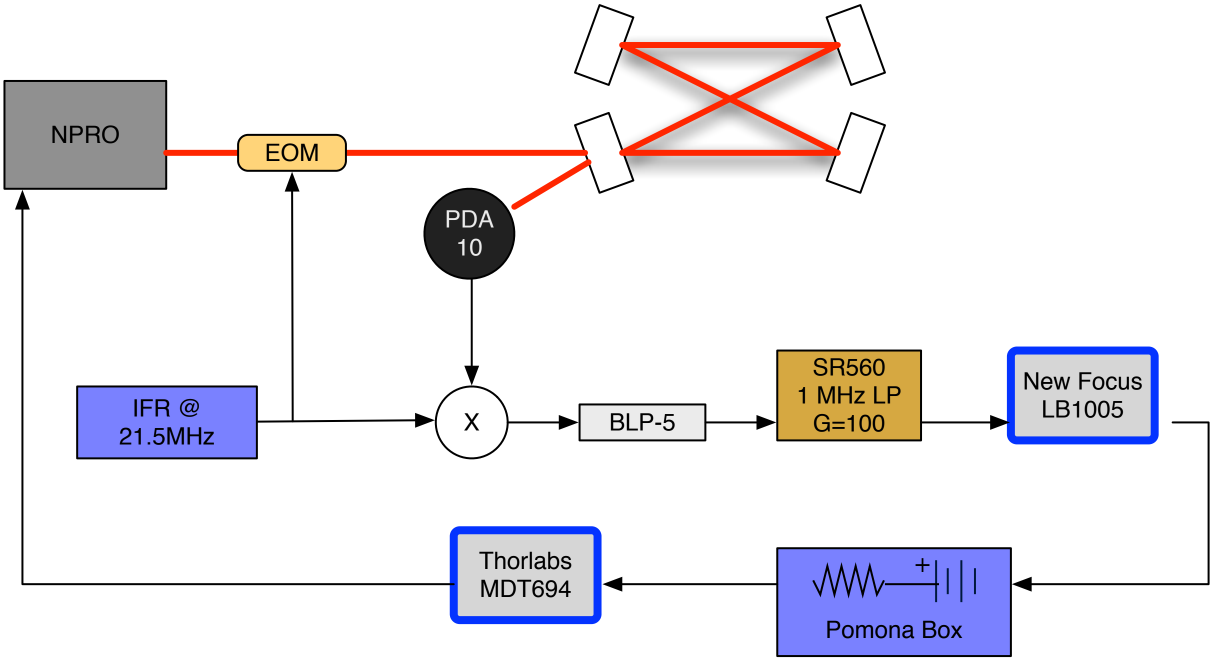

Figure 1: The electronics configuration for locking the laser to the OMC.

The power incident on the OMC was controlled using a waveplate and a polarizing cube. For small power levels, a 98% beamsplitter was used to divert most of the light.

2.2 Transmission measurements

The transmission measurements were made with the laser locked to the cavity. There was a strange coupling between the laser power and the PZT amplitude which may have resulted from using the polarizers to achieve extreme power extinction. This required a measurement of all powers simultaneously. Consequently, we installed pick off photodiodes at the input, in reflection, and in transmission. We measured all three photodiodes while the OMC was both on and off resonance to measure the power transmission.

2.3 Finesse measurements

The finesse was measured via two methods, here called *slow* and *fast*. In the slow method, the laser temperature was stepped by a large amount so the OMC would sweep through fringes. The fringe signal was recorded and the fringes fit offline using a Matlab program. In the fast method, the laser PZT is swept at 1, 10 or 100 Hz with a ramp waveform large enough to sweep across the fringe. The time between the carrier and RF sidebands was read off directly from an oscilloscope, as was the FWHM of the carrier fringe. Together, these allow for a calculation of the Finesse using the previously measured Free Spectral Range (FSR) of 278 MHz [6].

Unfortunately, the oscilloscope method of Finesse measurement suffers from a tricky systematic. Digitization bit noise limits the resolution of a voltage measurement (much of the data we took). This gave erroneous readings for the finesse - mostly low readings. Instead, the spacing between the career and RF, as well as the width of the FWHM, must be measured in *time* as described above.

3 Repair

Several things were tried to improve the OMC finesse. First, the transmitted power was measured, as described below. Second, each optic was photographed with an IR sensitive camera with fixed aperture and shutter speed. This identified the OTAS and PZT mirrors as large scatterers, and the OTAS mirror as having a secondary glint from the edge of the tube.

First, the OTAS and PZT mirrors were wiped with a Q-tip covered in lens-paper and dipped in methanol. No changes in the transmission were seen.

Second, the OTAS screws were loosened and the mirror shifted towards the center of the OMC (to the left when seen from behind). This resulted in a decrease in the transmission from 60% to 37%.

Finally, the OTAS screws were loosened and the mirror shifted away from the center (to the right when seen from behind). This resulted in an increase in the transmission to 95%, comparable to the "before change" values.

4 Measurements

After repairing the cavity, we performed three measurements: transmission, finesse, and transmission as a function of power.

4.1 Transmission measurement

The data taken for the transmission measurement is summarized in Table 1. Thus the power transmitted through the cavity is 0.36/0.38 = 95%.

Parameter	Value
Input power	0.55 mW
Transmitted power	0.36 mW
Reflected power (locked)	0.16 mW
Reflected power (unlocked)	0.54 mW

Table 1: Transmission data

4.2 Finesse measurement

The finesse was measured with 0.5 mW incident on the OMC, and the blowers turned off. The Finesse was measured with a ramp of 1 Hz and 10 Hz and comparable values found for both measurements. For the 10 Hz sweep, the time between the sideband resonances was 17.68 ms, while the FWHM of the carrier peak was 336 μs. Using the sidebands as a calibration, the FWHM is $0.336/17.7 \times 43 = 0.82\ MHz$. With a free spectral range of 278 MHz, the finesse is $\mathcal{F} = 278/0.82 = 340$.

4.3 Power scaling

Sheon measured the OMC transmission as a function of the total power in the low loss state. The data originally showed a surprising bimodality: we repeatedly measured high transmission of 95% with 0.5 mW incident on the OMC, but for higher powers of 5 mW and 50 mW, we measured a transmission of 85%. The data requires some interpretation. The most likely scenario was that the laser was running multimode with two dominant frequencies, only one of which was resonant. However, this situation was addressed by changing the power control and the laser temperature. The final data with a single mode laser is presented in Figure 4.3.

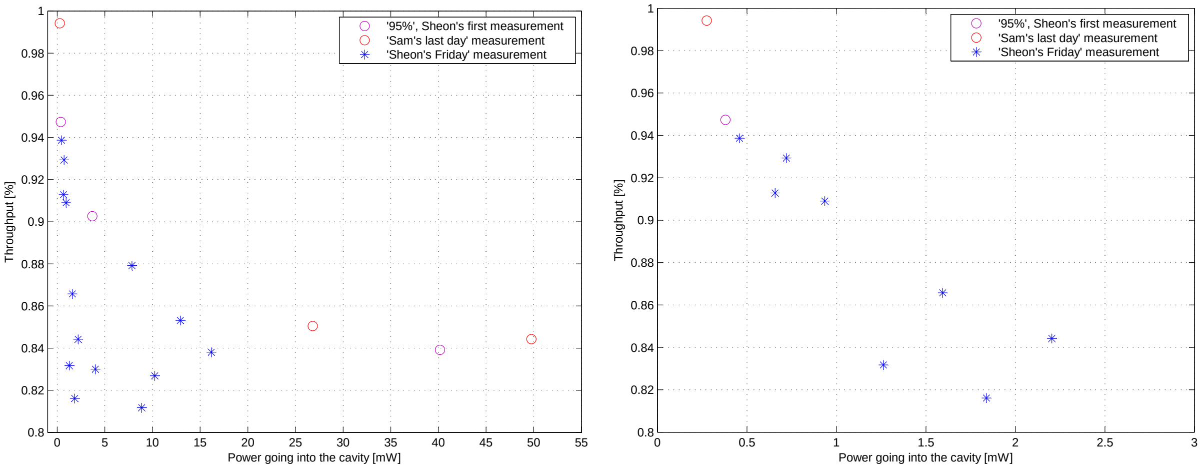

Figure 2: The OMC transmission depends strongly on the power incident on and circulating in the cavity.

The OMC shows a clear dependence on the power. The measurement apparatus was adjusted repeatedly, but the result remains.

5 Discussion

We measured the performance of the Hanford OMC at 95% transmission at low power. Likely, the problem was clipping on the OTAS entrance aperture. The thermal cycling due to the power outage likely caused a “creep” event that shifted the cavity alignement and exacerbated the loss. Moving the OTAS reduced the clipping. There is still an excess loss, 5%, that could be mitigated by shimming the OMC if desired.

The finesse and transmission are related by

$$\frac{P_T}{P_0} = \left(\frac{T\mathcal{F}}{\pi}\right)^2 .$$

The LHO OMC has a coupler transmissivity of $T = 8,300\ ppm$ as reported in [6]. For the Finesse reported here, the calculated transmission is only $P_T/P_0 = 80\%$. Alternately, the transmission reported here implies a Finesse of 370. Although these numbers are in contradiction, it is likely that the FWHM reported above is an overestimate due to motion of the laser frequency during the sweep, and the Finesse is, in practice, closer to 370 than to 340.

The power dependence of the loss is likely due to clipping changing with temperature. As shown in Figure 3, 95% transmission corresponds to a round trip loss of 400 ppm, while 84% transmission corresponds to 1400 ppm.

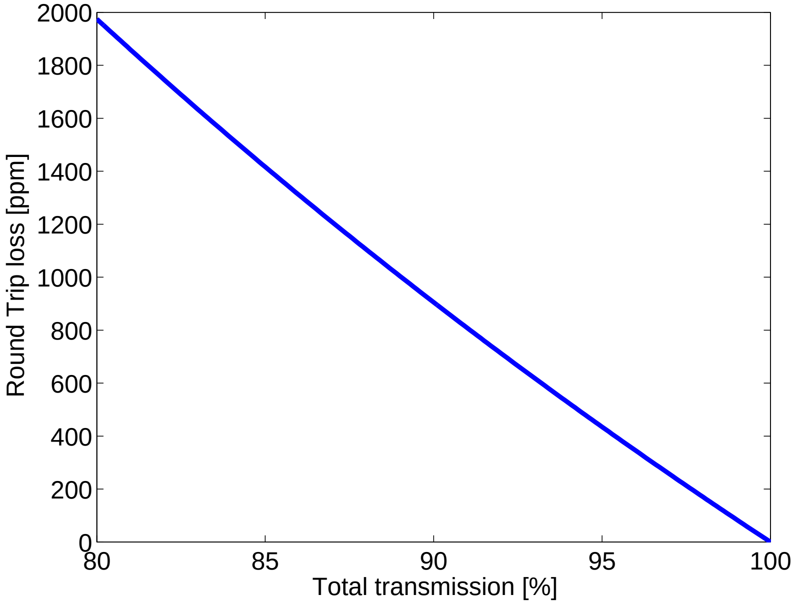

Figure 3: The round trip loss as a function of the transmission.

The most likely source of such a loss (both the static and power dependent), is the clipping at the thermal actuator. As shown in Figure 4, to account for this shift in loss would require translating a hard edged aperture by almost 100 μm, from 840 to 740 μm. Assuming the material is aluminum with a CTE of 13 ppm and a 1 mm zone of influence, the temperature rise is an enormous 7,000 K.

Similarly, to generate a mode mismatch of 10% by detuning the cavity mode would require a change in the waist size from $\approx 150\mu m$ with respect to the nominal $\approx 500\mu m$ waist size. This seems equally unlikely as it requires an enormous change in the mirror ROC (eg. both

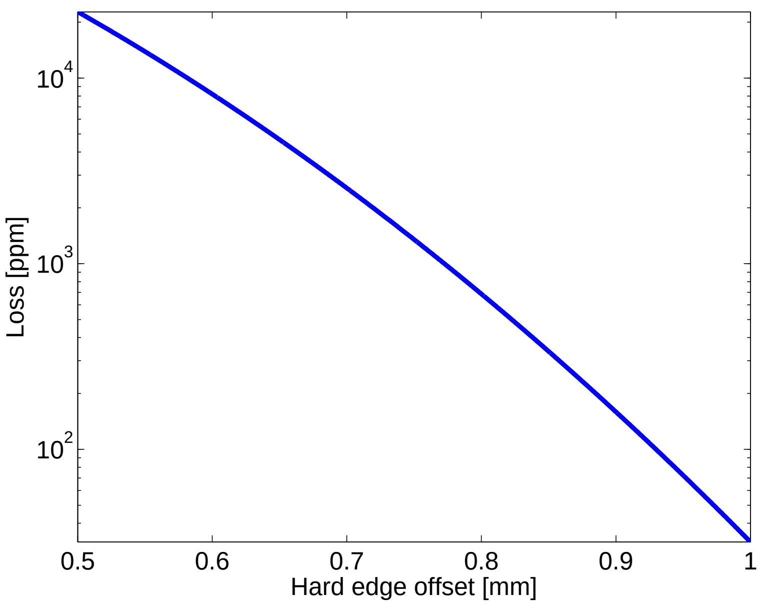

Figure 4: The round trip loss of the cavity as a function of a hard edged, one-dimensional aperture similar to the inner edge of the OTAS.

mirrors shift from R=2 m to R=1 m. So we can rule out the simplest absorption induced ROC as the origin of the mode match.

Obviously, we are at a loss to explain the origin of the increased loss in the LHO OMC at high incident power.