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Hanford 2k PSL Intensity Noise

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PSL, Detector

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1 ABSTRACT

The radio frequency intensity noise of the prestablized laser (PSL) of the Hanford 2km interferometer was measured on 15 Dec 1998 as part of the validation process for the PSL. The measurement is broadband, 100kHz-100MHz, the detector a modification of the LSC design. We find that the configuration of having the intensity servo (ISS) after the pre-modecleaner (PMC) introduces significant amounts of excess noise and the overall required noise performance of the PSL may not be met.

2 KEYWORDS

PSL, RF-AM, Intensity Noise, Power Noise, Noise.

3 OVERVIEW

We discuss the detector developed to measure the PSL intensity noise and the results obtained.

4 INTRODUCTION

One of many sources of noise in the LIGO interferometer is laser amplitude noise, or intensity noise. Document xxx discusses the propagation of this and other forms of noise from the laser to the dark port when the interferometer it is on resonance. The required limit of the PSL is to provide a beam which, at the length sensing RF modulation frequency, is not more than 1.005 times the shotnoise limit of a 600mW beam. This is the expected power at the dark port. We make our-measurements with about 142mW of optical power, and extrapolate the measured noise spectrum to 24.5 MHz. Measurements are made at the PSL output as well as just before the pre-modecleaner. We compare the two and find the filtering performace of the PMC to be close to a single pole filter at 3.3MHz.

5 THE DETECTOR

5.1. History/ LSC Design

5.2. Circuit Diagram

5.3. Performance

5.3.1. Frequency Response

5.3.1.1 Optical

5.3.1.2 Electronic

5.3.2. Noise Performance

5.3.2.1 Prediction

5.3.2.2 Measurement

6 MEASUREMENTS

6.1. Setup

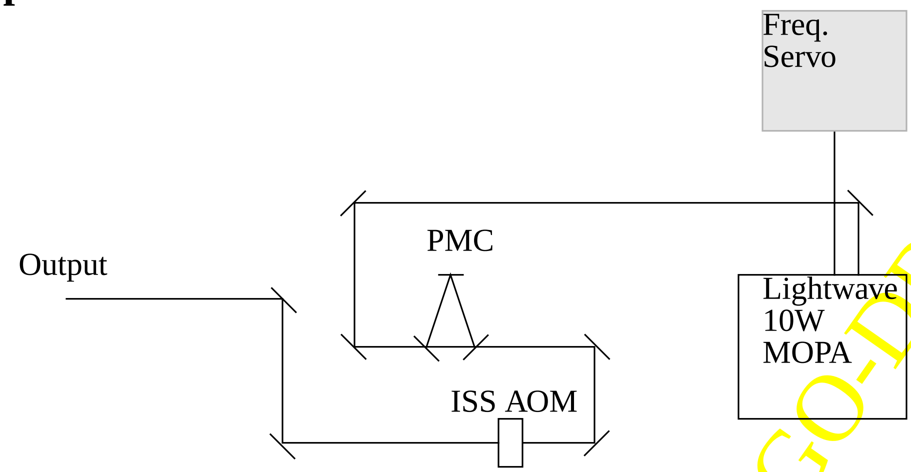

Figure 1: Schematic setup of the PSL during the intensity noise measurements.

Figure 1 outlines the setup of the PSL during our measurements. All servo parameters were adjusted to their nominal values. Of particular note is that the intensity servo acousto optic modulator was located after the pre-modecleaner.

6.2. Measurements

We take both power spectra and power spectral densities with an HP 4395A Network/Spectrum analyzer. We distunguish between the two for the following reason: in ‘Spectrum mode’ the analyzer uses a peak-detect algorithm that yields a noise spectral density that can be up to 6dB higher than a ‘Noise mode’ measurement of the same signal. Additionally, in ‘Noise mode’ the analyzer picks discrete frequencies to measure at, missing peaks that fall between these points. The power spectra are taken in linear frequency axis mode (the only mode supported by the analyzer) with 801 data points. We choose two frequency bands to measure all signals in: 0-10 MHz and 10-100MHz. From 0-10MHz we use a single zero filter (a 200pF capacitor in series with the analyzer input) to whiten the signal and avoid overloading the analyzer input stage or having to raise the input attenuation.

In addition to the above frequency intervals we take spectra centered on some of the larger peaks we observe.

We also take time-domain data for later analysis of the stationary nature of the noise. Appendix 1.

6.3. Analysis

We list some of the quantities used in analyzing the data:

$n_D(f)$: spectral density of the noise in the detector ($V/\sqrt{Hz}$).

$n_{HP}(f)$: spectral density of the noise in the analyzer ($V/\sqrt{Hz}$).

$P_\nu(f)$: spectral density of intensity noise in the sampled beam ($W/\sqrt{Hz}$).

$P_{Shot}(f)$: spectral density of shot noise of the sampled beam ($W/\sqrt{Hz}$).

S : Sensitivity of the photodiode (A/W).

$H(f)$: Transfer function of the detector (V/A).

$F(f)$: Transfer function of the whitening filter.

With these definitions, the signals that we measure are assumed to be:

Dark noise: $Dark(f) = \sqrt{n_D^2(f) + n_{HP}^2(f)}$.

Dark noise with whitening filter: $Dark_{filt}(f) = \sqrt{n_D^2(f)F^2(f) + n_{HP}^2(f)}$

Measured signal: $V_{out}(f) = \sqrt{S^2H^2(f)[P_\nu^2(f) + P_{Shot}^2(f)] + n_D^2(f) + n_{HP}^2(f)}$

Measured signal with whitening filter:

$$V_{out-filt}(f) = \sqrt{\{S^2H^2(f)[P_v^2(f) + P_{Shot}^2(f)] + n_D^2(f)\}F^2(f) + n_{HP}^2(f)}$$

7 RESULTS

The power in the sampled beam is adjusted so that we always have 100mA of photocurrent in the detector. This corresponds to about 142 mW of optical power. Figure 2 shows a composite of the spectrum measurements, with detector noise removed:

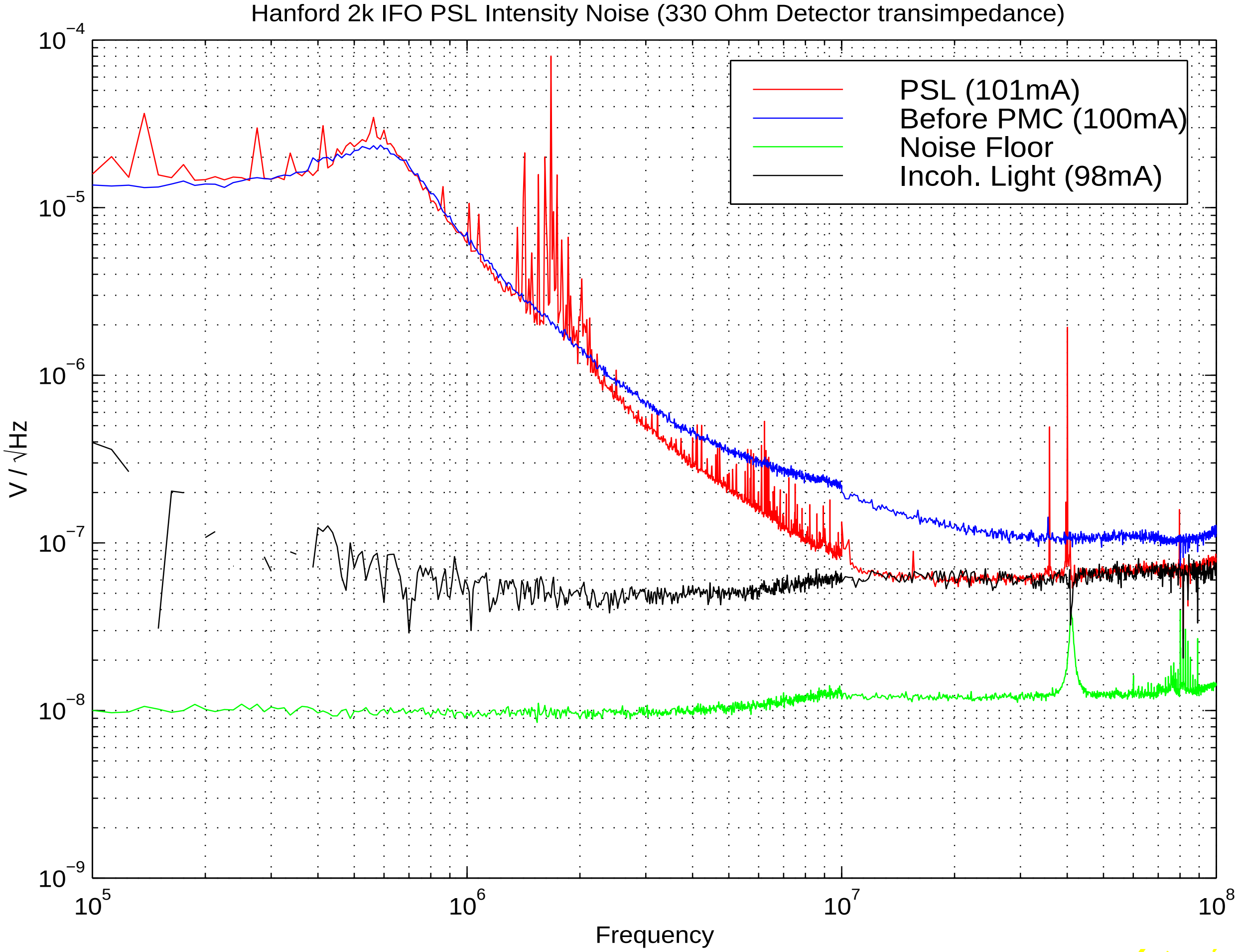

Figure 2: Intensity noise spectrum of the Hanford 2k PSL on 15 Dec 1998. Also shown are the shotnoise level for the same amount of light and the dark noise level for the detector.

For completeness we also include plots of the above spectra on a linear frequency scale, as they were taken (figures 3 and 4.)

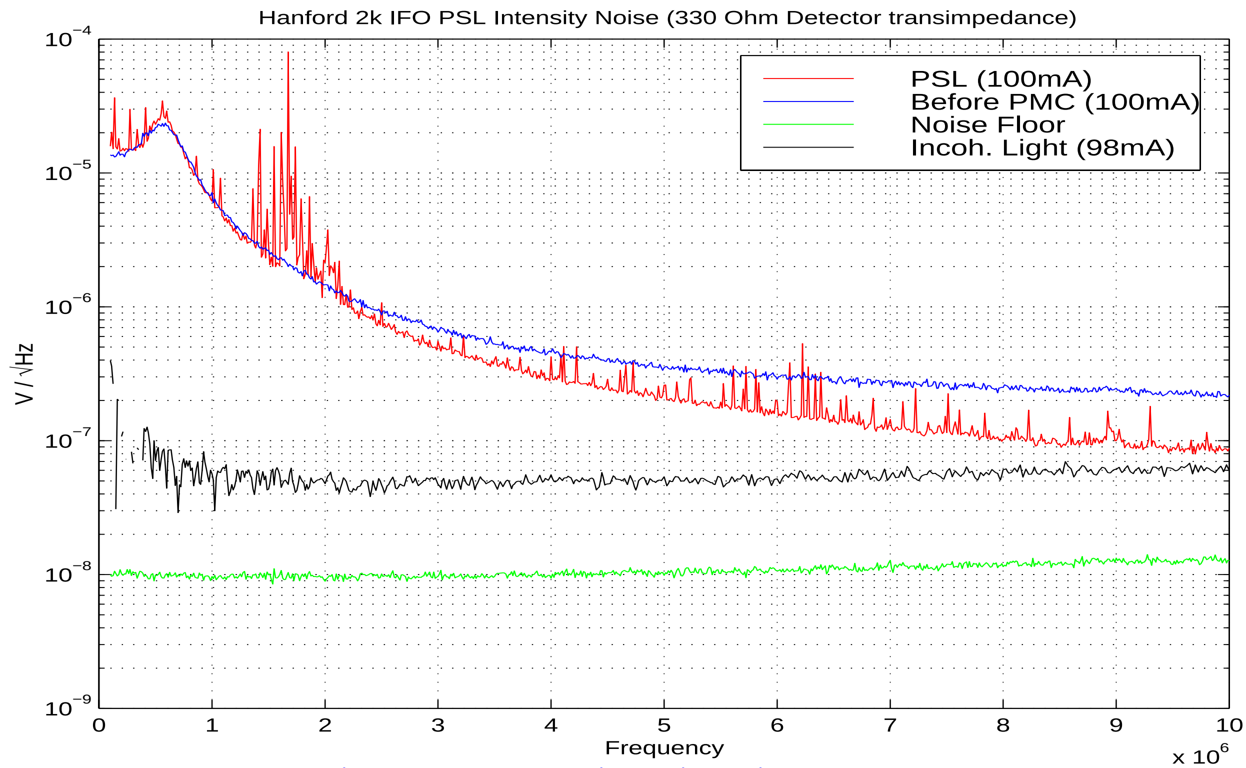

Figure 3: 0-10 MHz intensity noise spectra.

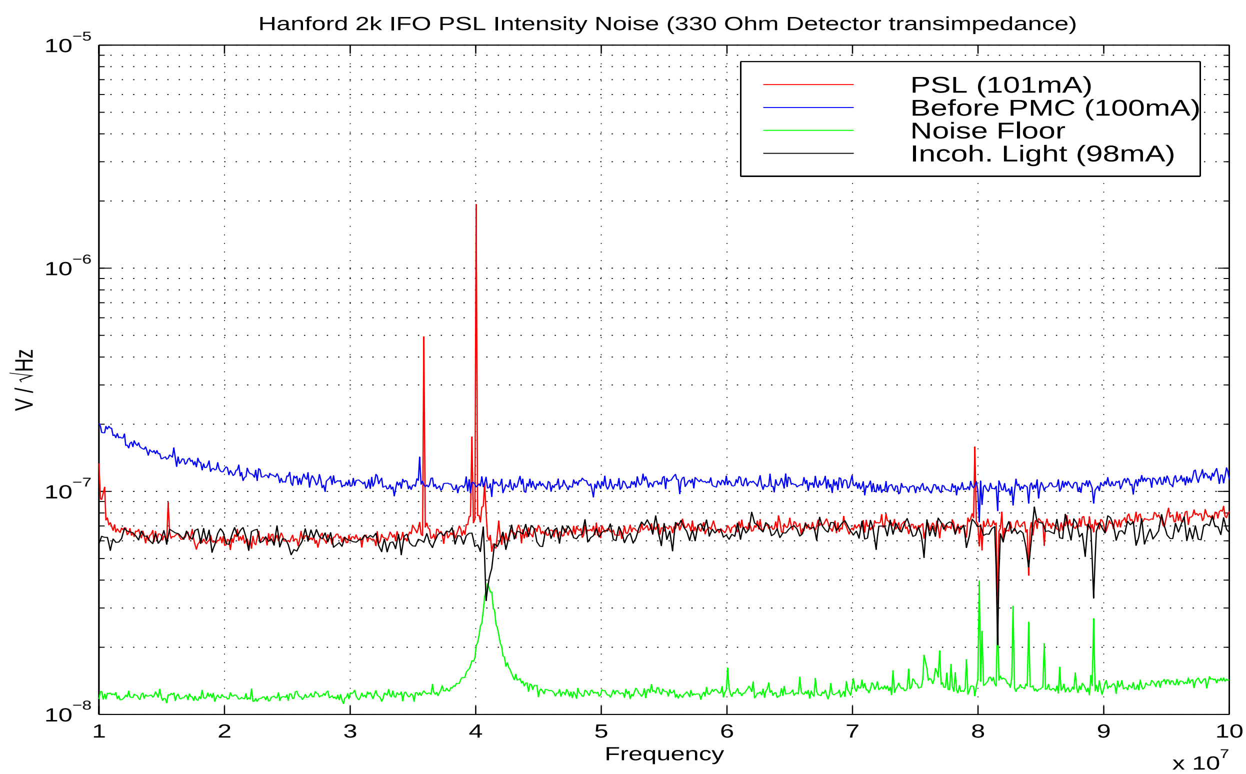

Figure 4: 10-100 MHz intensity noise spectra.

The composite spectrum taken with the analyzer in ‘spectrum’ mode is shown in figure 5. The

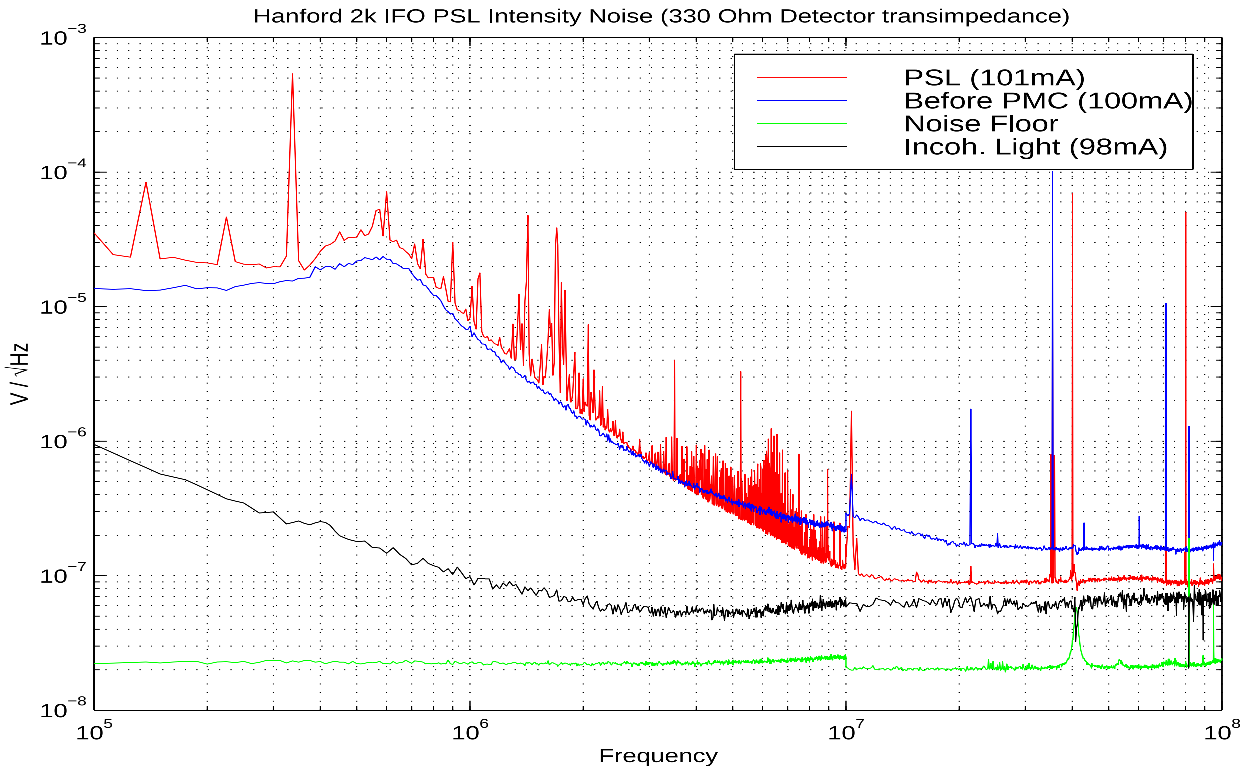

Figure 5: Noise spectrum taken in ‘spectrum mode’. Cearly shows more peaks than figure 2.

same data on a linear frequency axis are shown in figures 6 and 7, clearly showing a larger density of peaks in the signal at the output of the PSL than in the ‘noise’ mode plots above.

8 CONCLUSIONS

8.1. PSL Topology

We find a lot of noise peaks at frequencies up to 10MHz in the PSL output which are notably absent from the spectra of light incident on the pre-modecleaner. We suspect that this is due to the placement of the intensity servo acousto-optic modulator at the PSL output. This element should be placed before the PMC.

8.2. PMC performance

By dividing the noise spectrum of the light at the PSL output by the spectrum incident on the PMC, we find the transfer function for intensity noise of the PMC. The resonance bandwidth of the cavity as seen from figure 8 is close to the expected 3.3 MHz[1]. However, due to the fact that the master oscillator is *not* shotnoise limited at 24.5 MHz, the overall PSL intensity noise specification may not be met (see below.)

1. See *PSL Conceptual design*, LIGO document T970087-04, page 40-41.

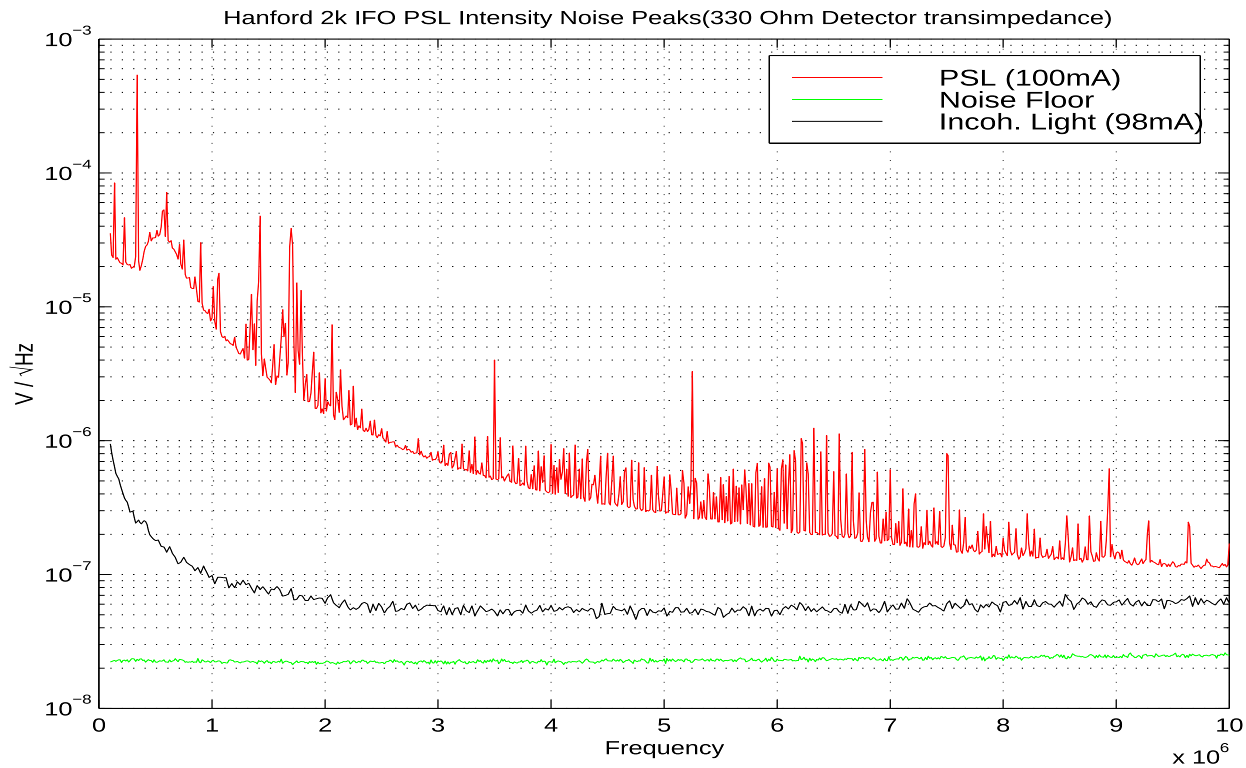

Figure 6: 0-10MHz intensity noise in the PSL output.

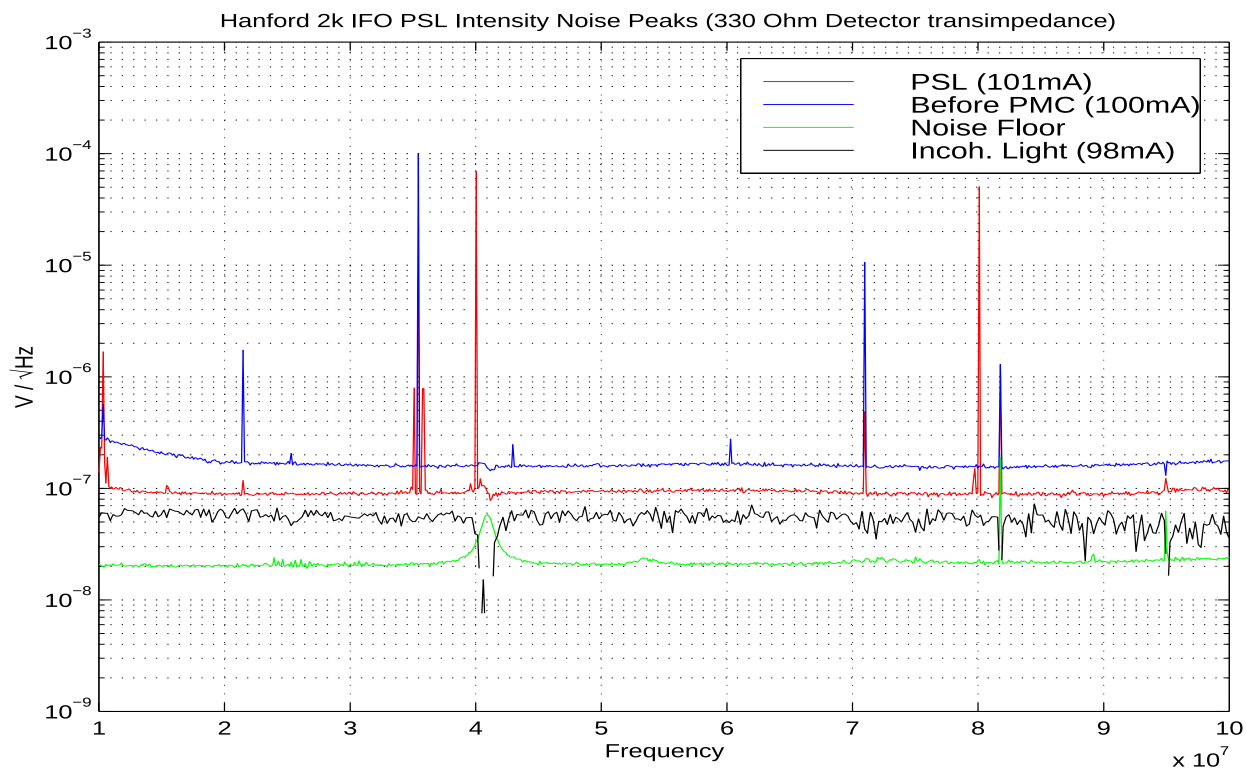

Figure 7: 10-100 MHz intensity noise of the PSL. (Spectrum Mode)

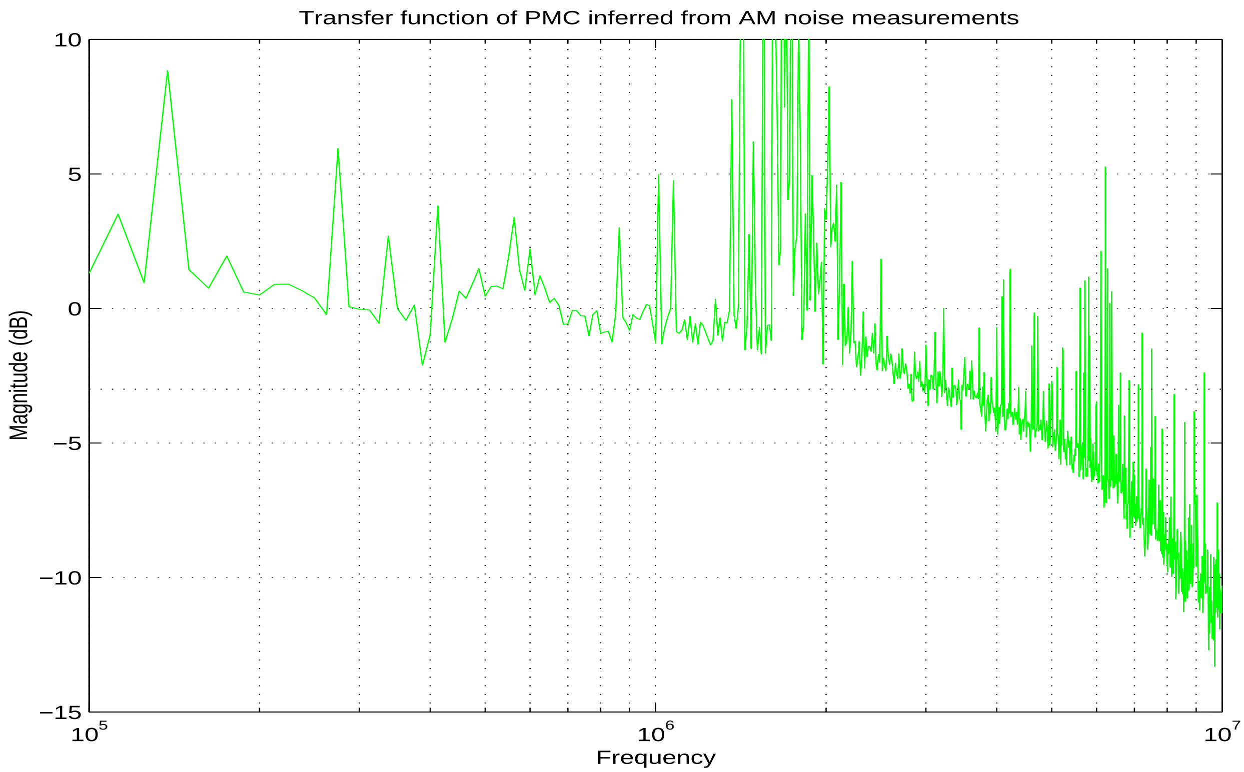

Figure 8: PMC transfer function derived from spectrum measurements. The extra dotted line indicates the -3dB level.

8.3. Intensity Noise at the Modulation Frequency

We extrapolate the measured PSL noise spectrum between 3 MHz and 8.5 MHz up to the the LSC modulation frequency of 24.5 MHz to estimate the noise for a 600mW beam. We first subtract the shot noise contribution and then remove the peaks in the noise spectrum using a simple algorithm that allows successive data points to differ in value by some maximal amount. We then make a linear fit to the logarithm of the data as a function of the logarithm of the frequency. The results are shown in figures 9 and 10. If we now assume that the non-shotnoise component of the intensity noise scales linearly with power, we can make an estimate for the noise of a 600mW beam: at 24.5 MHz, for 142mW of optical power, the fit to the intensity noise spectrum gives $1.3 \times 10^{-8} V/\sqrt{Hz}$ of detected signal, and the shot noise is $6.2 \times 10^{-8} V/\sqrt{Hz}$. Scaling the fitted value by $600/142 = 4.2$ and the shot noise by the square-root of this value (2.05), we estimate the ratio of noise spectral densities will be:

$$\frac{P_{\nu}^{600mW}(f)}{P_{shot}^{600mW}(f)} = 0.43$$

This means at the output of the PSL the shot noise is only 3.7 dB above the laser noise, or that the output noise is 1.09 times the shotnoise limit of 600mW, exceeding the specification of 1.005. We need an additional attenuation of approximately 6.3 dB. Placing the the pre-modecleaner resonance at 2 MHz as suggested[1], would yield an additional 8.6 dB of noise attenuation satisfying the requirement. We think a measurement at the full 600 mW is needed for convincing proof.

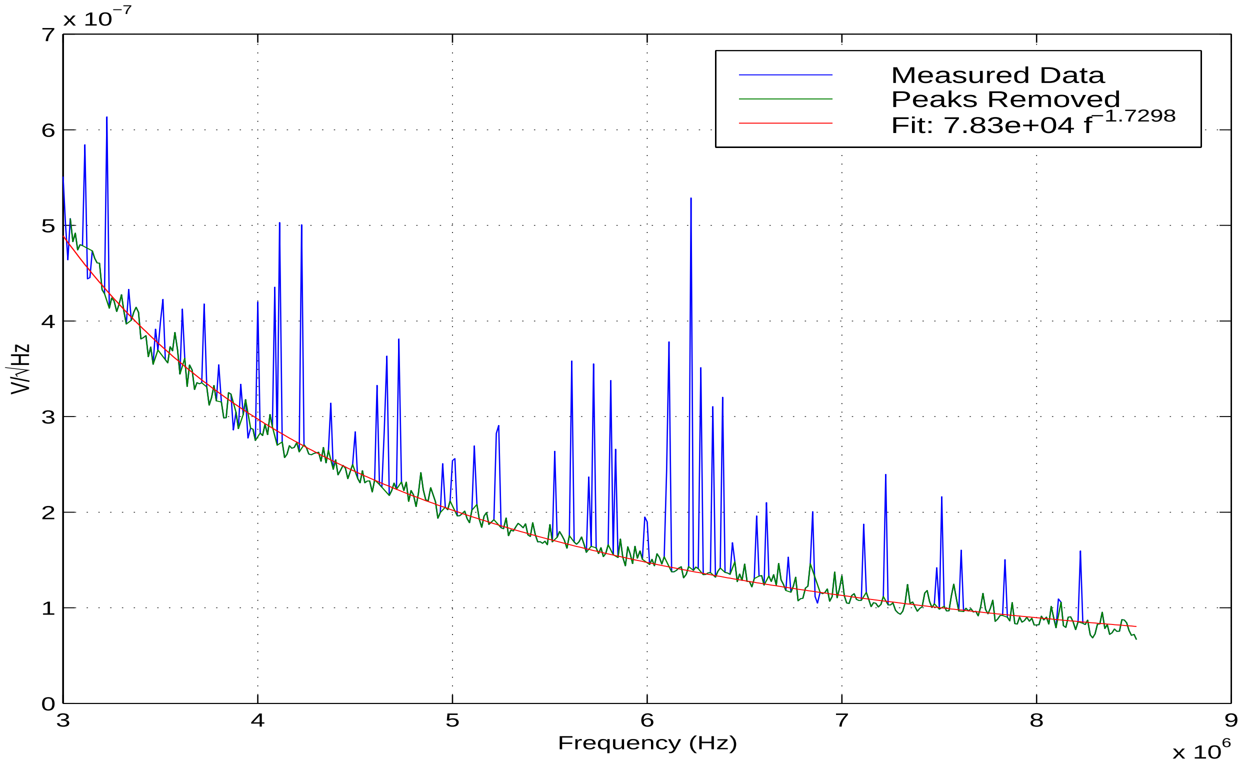

Figure 9: Fit to the intensity noise spectrum.

8.4. High Frequency Noise

The propagation of noise from the master oscillator through the power amplifier to the detected beam is described by the equation[1]

$$\left(\frac{P_{output}(f)}{P_{shot}(f)}\right)^2 = 1 + \eta\left\{H\left[\left(\frac{P_{\nu}^{MO}(f)}{P_{shot}^{MO}(f)}\right)^2 + 1\right] - 2\right\}$$

Here $P_{output}(f)$ is the amplitude spectral density of intensity noise at the output of the system, $P_{\nu}^{MO}(f)$ is the amplitude spectral density of intensity noise of the master oscillator, H is the power gain of the amplifier, η is the fraction of light detected at the output.

Let us estimate the right hand side of the above equation for our setup. Looking at figure 7, and assuming that the master oscillator is shot noise limited between 45 MHz and 75 MHz (where the noise measured before the pre-modecleaner is spectrally flat) we take

$$\frac{P_{\nu}^{MO}(f)}{P_{shot}^{MO}(f)} = 1 .$$

1. *PSL Conceptual design*, LIGO document T970087-04
1. ibid, Appendix 3.

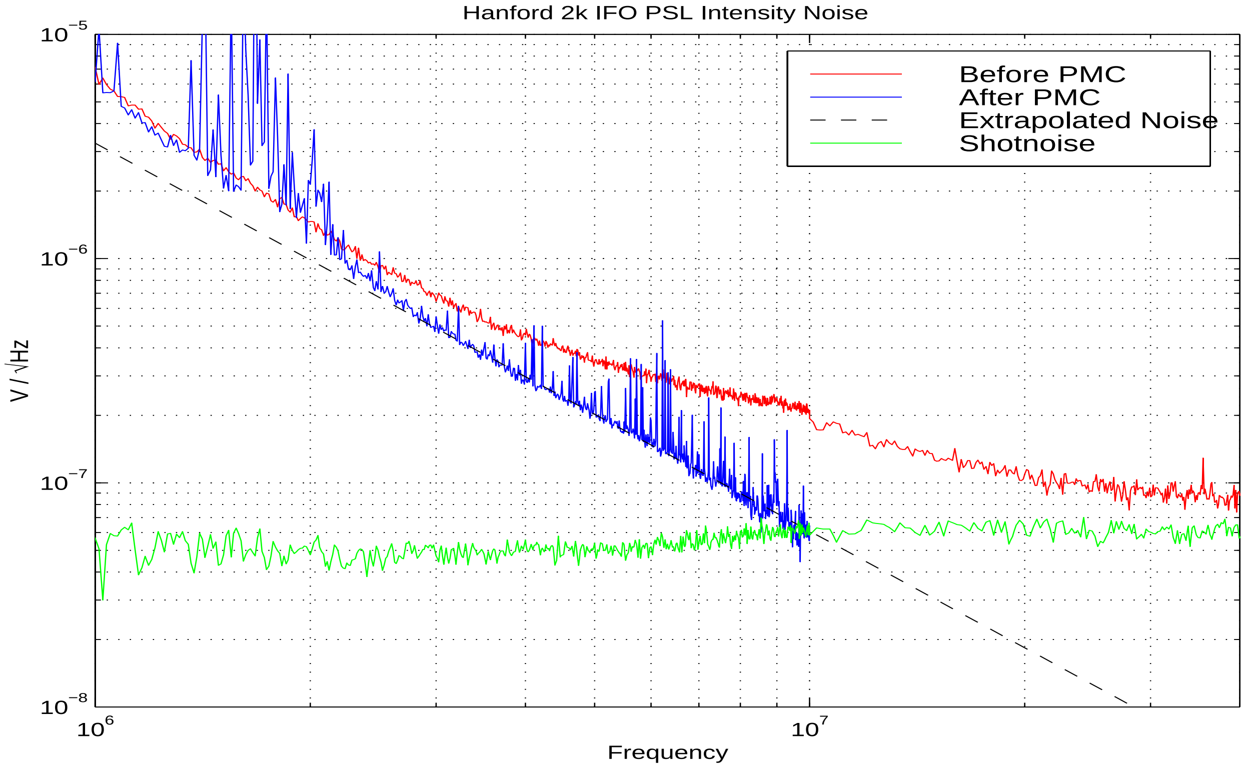

Figure 10: Extrapolation of the intensity noise to higher frequenies.

The MO power was approximately 500mW, the MOPA output about 10W, so we take H to be 20. For η we take the fraction of light measured (142mW/10W) times the diode quantum efficiency (82%) to get 0.0116. Thus we estimate the relative power fluctuations should be $\frac{P_{output}(f)}{P_{shot}(f)} \approx 1.20$

Taking the average of the spectra in figure 7 between 45 and 75 MHz, we find the measured ratio to be 1.62. While some of the above parameters were unfortunately not measured accurately, it is hard to see how we can adjust them to come up with a result as high as 1.62. It is therefore possible that there is another source of noise.

APPENDIX 1 TIME DOMAIN MEASUREMENTS

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