LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Final Report: Automated Photodiode Frequency Response Measurement System for Caltech 40m lab

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1 Introduction

LIGO (Laser Interferometer Gravitational wave Observatory) is designed to detect gravitational waves using laser interferometry. This project is carried out at the Caltech 40m prototype interferometer lab, or simply 40m Lab, which functions as an R&D facility for LIGO.
The 40m houses a Dual Recycled (signal and power) Fabry-Perot Michelson (DRFPMi) Interferometer. Each arm of the interferometer consists of two mirrors that form an optical cavity. Several photodiodes are used to sense various degrees of freedom and provide feedback signals to position the mirrors for correct operation of the apparatus and ensure that cavity resonances are acquired and maintained. In addition, the main interferometric gravitational wave signal is also read out with a photodiode.
Hence, it is necessary to ensure that the detector can be controlled and read out optically. This is the motivation factor for our project.
The goal of this project is to treat the photodiodes and their readout electronics as systems whose performances can change with time and operating conditions and build an automatic frequency response measurement system to measure them.

2 Objective

Photodiodes are essential sensors at the 40m lab as described above. This system will enable the lab personnel to check if a PD is faulty or not without entering the experimental lab, where their presence may disturb the detector. They can choose the required PD from a GUI interface to run the frequency sweep test, analyze the data and then bring up its current transimpedance frequency response plots.
The system has been dubbed PDFR (PhotoDiode Frequency Response).

3 Transimpedance calculation - Reference PD method

The output of the PD under test is compared to a known Reference PD to make sure that any variations in laser output power are normalized out.

$$DC output voltage = Photocurrent * DC transimpedence \tag{1}$$

$$V_{DC,Ref} = I_{DC,Ref} * T_{DC,Ref} \tag{2}$$

$$V_{DC,Test} = I_{DC,Test} * T_{DC,Test} \tag{3}$$

$$RF output voltage = Modulation depth * Photocurrent * RF transimpedence \tag{4}$$

$$V_{RF,Ref} = \epsilon(f) * I_{DC,Ref} * T_{RF,Ref} \tag{5}$$

$$V_{RF,Test} = \epsilon(f) * I_{DC,Test} * T_{RF,Test} \tag{6}$$

(a) $T_{DC,Ref}$ and $T_{DC,Test}$values from the datasheet are assumed to be accurate.

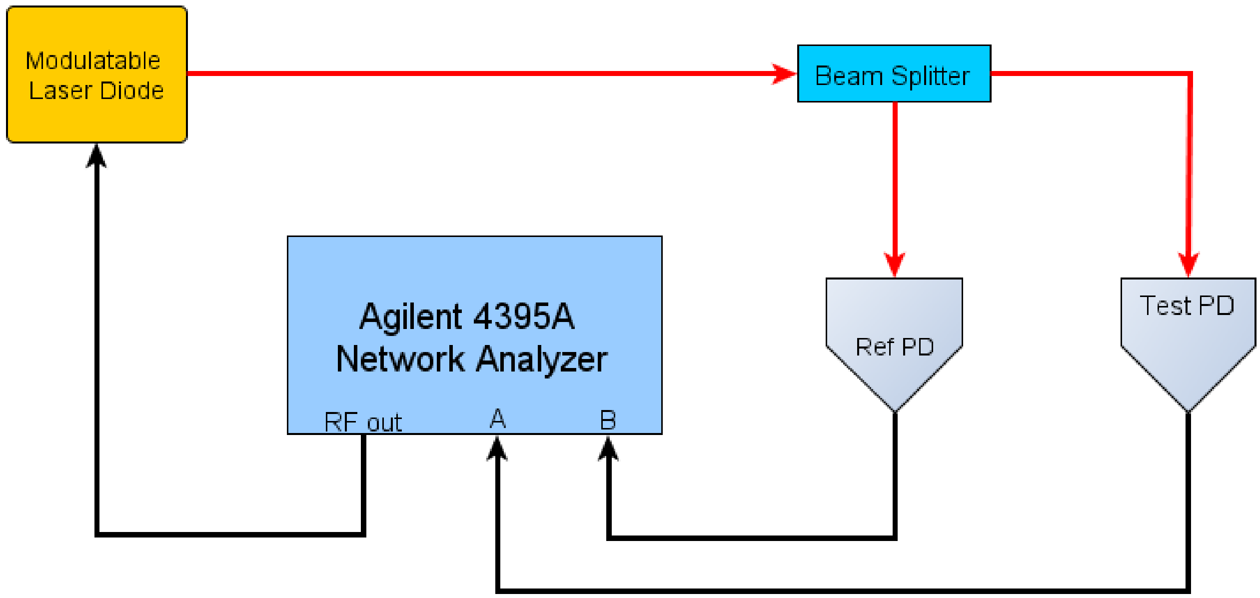

Figure 1: Block diagram of setup to calculate transimpedance using the reference PD method. The Diode laser is modulated by the network analyzer's swept sine wave. A commercial broadband photodiode is used as the reference. The output of Test PD is then recorded relative to the reference PD.

(b) $T_{RF,Ref}$value from the datasheet is also assumed to be accurate as the Ref PD is designed to be operated over a very large frequency range, in this case 30kHz to 1GHz, and we sweep frequencies which are well within this range (1MHz to 300MHz or so).

(c) Dividing equation [6] by equation [5]

$$\frac{V_{RF,Test}}{V_{RF,Ref}} = \frac{I_{DC,Test}}{I_{DC,Ref}} * \frac{T_{RF,Test}}{T_{RF,Ref}} \tag{7}$$

(d) From equations [2] and [3]

$$\frac{V_{RF,Test}}{V_{RF,Ref}} = \frac{V_{DC,Test}}{V_{DC,Ref}} * \frac{T_{DC,Ref}}{T_{DC,Test}} * \frac{T_{RF,Test}}{T_{RF,Ref}} \tag{8}$$

$$T_{RF,Test} = \frac{V_{RF,Test}}{V_{RF,Ref}} * \frac{V_{DC,Ref}}{V_{DC,Test}} * \frac{T_{DC,Test}}{T_{DC,Ref}} * T_{RF,Ref} \tag{9}$$

(e) $\frac{V_{RF,Test}}{V_{RF,Ref}}$ is the value measured from the network analyzer.

(f) $V_{DC,Ref}$ and$V_{DC,Test}$ values are measured with a multimeter.

(g) The values are plugged in and the RF transimpedence for the test PD is calculated at different frequencies.

4 The PDFR system

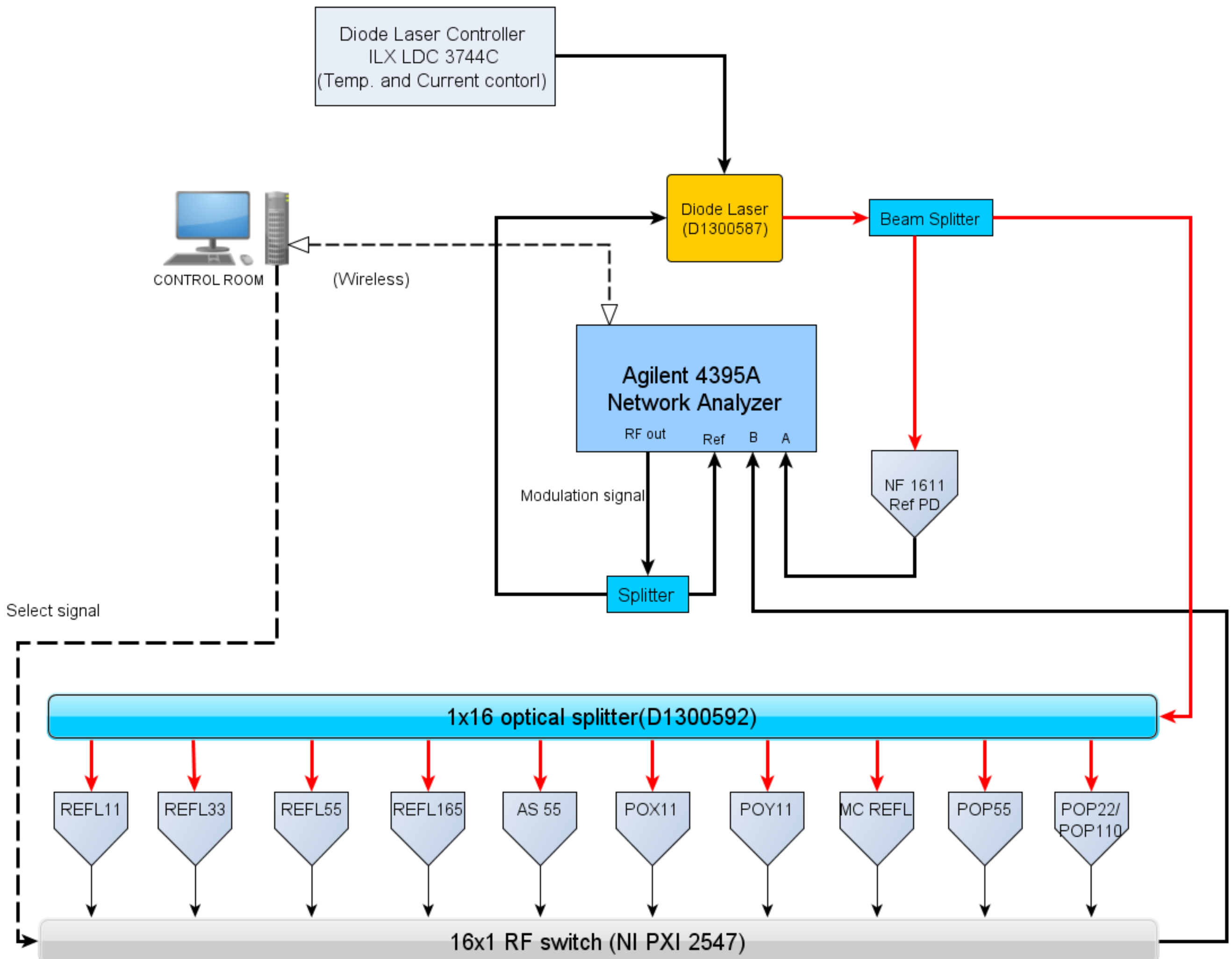

Figure 2: Block diagram of setup to measure transfer functions for a collection of photodiodes. The Diode laser is contorlled by ILX LDC 3744C and both of them along with the RF multiplexer are mounted on 1Y1 rack. The 1x16 optical splitter is used to illuminate all the photodiodes simultaneously. The required output from the PDs is selected by the RF multiplexer(NI PXI 2547) and sent to the control room computer. The network analyzer receives sweep commands and parameters from the control room and sends data back wirelessly

There are a total of 10 PDs that need to be sequentially analyzed. A diode laser, whose output power is amplitude modulated by its drive current, is used to illuminate the PDs. This laser requires 2 currents - a DC current to make it lase and a modulating signal to perform amplitude modulation. The modulation current is provided by a network analyzer (Agilent 4395A) and a diode laser controller (ILX LDC 3744C) is used to provide the DC current and also monitor its temperature. The diode laser's amplitude modulated output is divided using a 1x16 Optical Splitter and routed to separate PDs. The RF (Radio Frequency) output of each PD at the 40m lab is routed to a demodulator board. This demodualtor board is used in the `Pound-Drever-Hall` technique to lock `Fabry-Perot` cavities of the interferometer and is out of scope of this project. However the board has an output named PD RF MON (Radio Frequency Monitor) that just follows the input and is to be used for checking the PD. The PD RF MON output is attenuated compared to the actual output of the PD and our system needs to take this into account. The RF signal from each PD will be fed to the network analyzer using a 16x1 RF multiplexer, which allows us to select an individual PD.

The network analyzer produces a swept sine wave (modulating signal) over a range of preset measurement frequencies and measures the amplitude and phase response of the RF (Radio Frequency) output of the PD under test. This gives us the response of the PD across the range of frequency.It also divides the Test PDs output by the Ref PDs output to account for variation in laser output power and sends this transfer function data wirelessly to the control room computers, where the transimpedance values are calculated and plotted against frequency. These plots are then compared with canonical plots to check if the PD is still functioning as it should be. TCP/IP is used to communicate with the switch and inform it to move to the next PD after one set of data has been collected. The block diagram of the setup has been shown in figure 2.

5 Work Completed

1. Installation and verification of the whole setup
   (a) Verifying the proper working of single mode optical fibers to each PD and setting up optical collimators at the end of the fiber for focusing of light on the PD.
   (b) Routing RF coaxial cables from the demodulator boards to RF multiplexer at the 40m lab on overhead wire racks.
2. Computer scripts
   (a) Writing and testing of a script for acquiring data from the network analyzer wirelessly over GPIB(General Purpose Interface Bus). The script uses sweep parameters provided in a .yml file. The data obtained is stored as a .dat file and the corresponding details regarding the acquired data is in a .par parameter file.
   (b) Writing and testing of a script to program the RF multiplexer to the required channel over TCP/IP
   (c) Making a master script that takes in the PD name as input, automatically switches the RF Multiplexer to the required channel, acquires data and plots the transimpedance in a .pdf file.
   (d) Creating a MEDM graphical interface with buttons for each PD to run the frequency response scan and bring up the transimpedance plots.
3. Data analysis:
   (a) Documentation of the correct logic behind transimpedance calculation using a commercial PD as reference.

(b) Integrating the transimpedance calculation with the master script.

(c) Creating a database of DC measurements ($V_{DC,Ref}$ and$V_{DC,Test}$) for each PD that is needed to calculate transimpedance.

(d) Calibrate out the attenuation caused by demodulator boards by measuring it separately and modifying the measurements by that factor. Only then can correct readings be obtained.

(e) Create a canonical set of data, that shows transimpedance plots for a correctly functioning PD and integrate an option into the master script for comparison of the new data with the canonical data, leads to easy identification of errors in the PD.

(f) Scripts to generate plots that shows the fit of transimpedance to a transfer function model, using vector curve fitting. Vector Fitting is a robust numerical method to identify state space models directly from measured or computed frequency responses.

6 Output of the PDFR

The final system will now generate transimpedence plots for any of the required PDs based on which button is pressed on the GUI. Figure 3 shows a reading carried out for REFL11 photodetector.

7 Challenges faced

7.1 Dealy in RF cables

The signal from the PDs at the 40m had to travel on long RF cables (more than 10 meters). This lead to huge time delays between the Ref and A or B inputs to the network analyzer. Hence, the phase readings obtained became unintelligible.
The delay in each wire had to be calculated approximately and then calibrated out.

1. Transfer function for an ideal delay function : $T(s) = e^{-sT_d}$, where T_d is the time delay.
2. The slope of the phase gives the time delay.

Figure 4 shows the delay caused by a cable of 550m.

7.2 Attenuation in Demodulator boards

As mentioned before, the PD RF MON output of the demodulator boards is attenuated compared to the actual output of the PD. Hence, the exact amount of attenuation was calculated for each of the boards by making a reference signal to pass through it. The obtained attenuation characteristics were fit into a transfer function using vector fitting algorithm on Matlab. These transfer functions were then used to calibrate out the attenuation and get accurate results Figure 5 illustrates this for POP22 demodulator board.

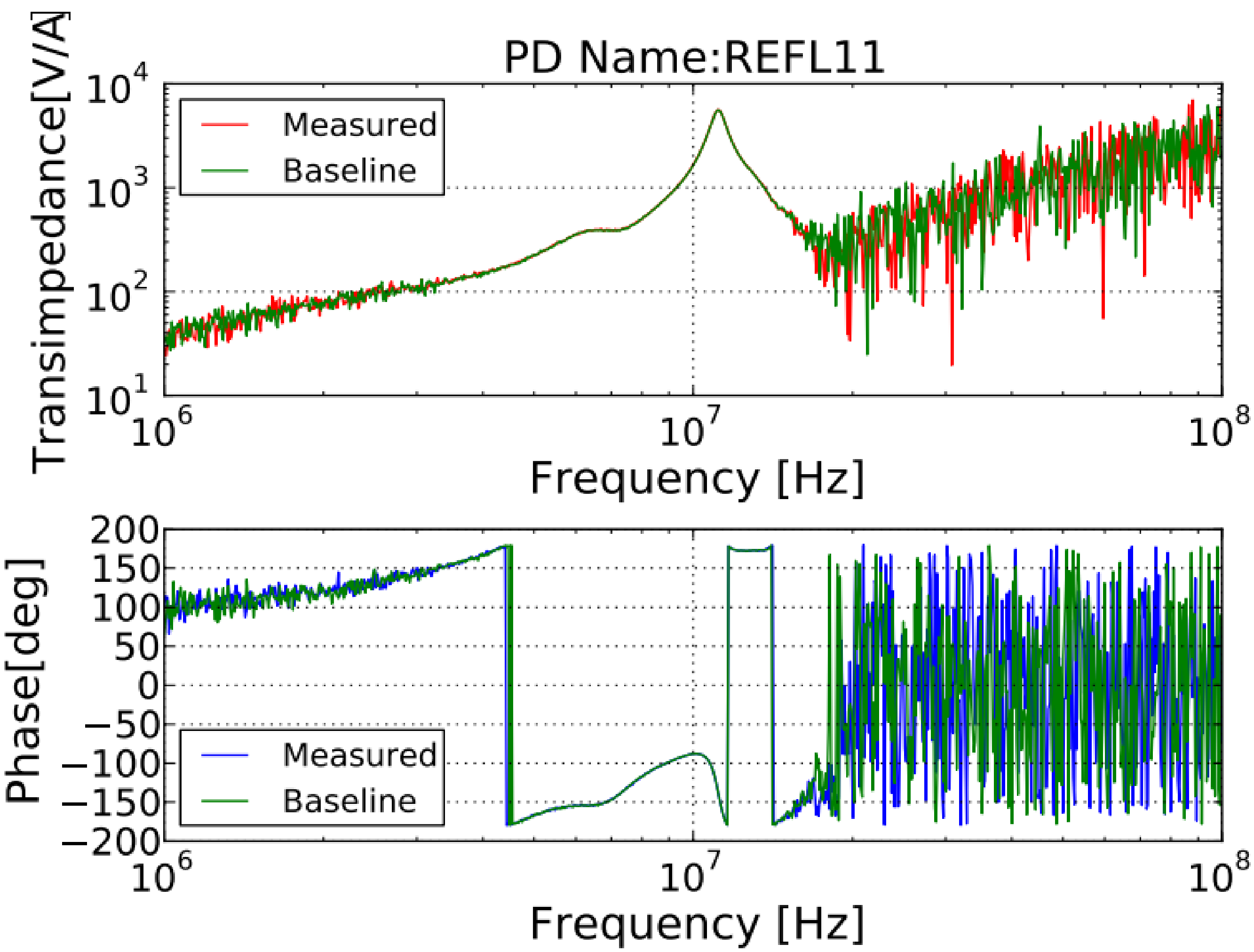

Figure 3: Plot of transimpedance for REFL11 photodetector. The transimpedence value obtained at 11MHz is in agreement with its designed value, provided in the 40m-wiki

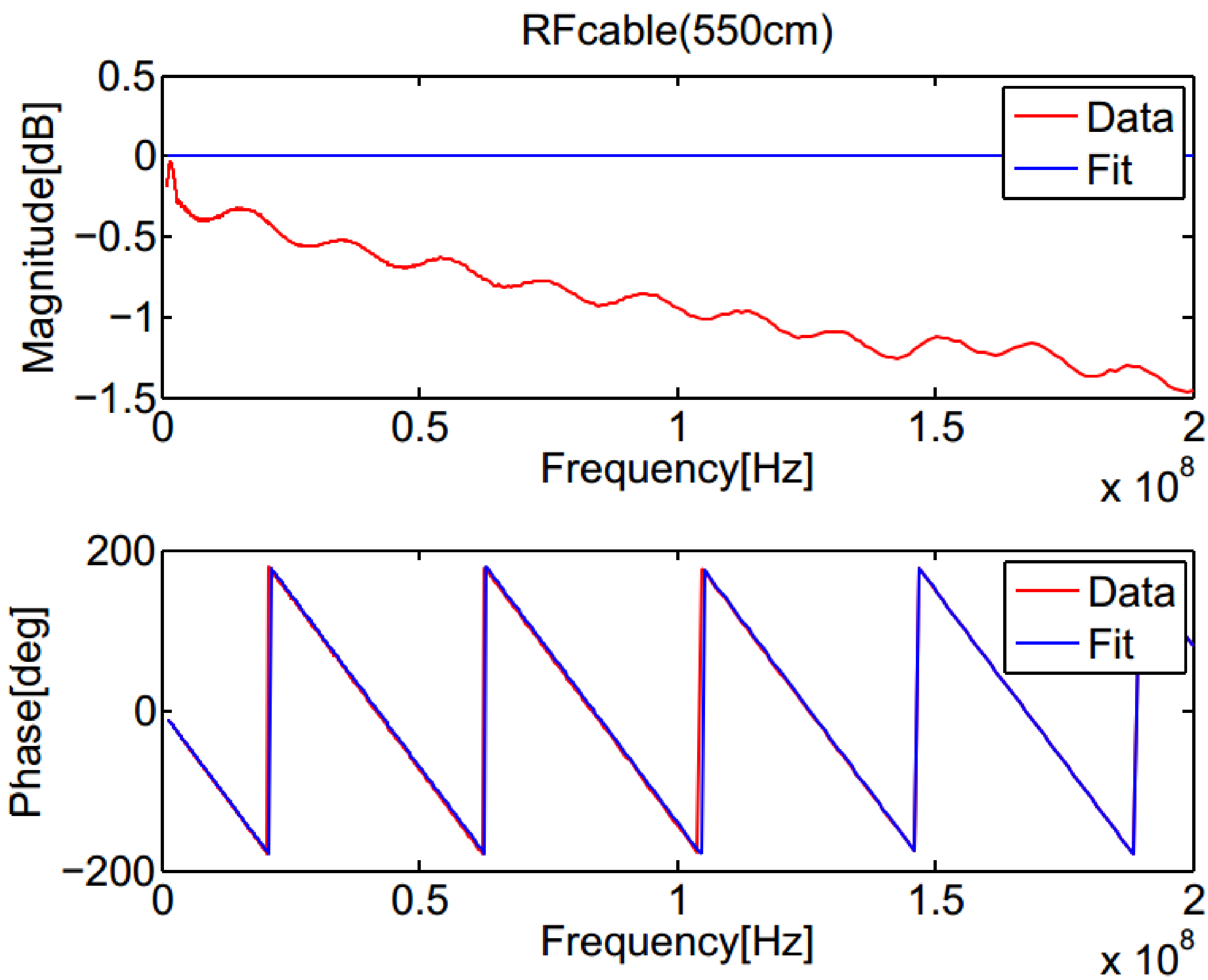

Figure 4: Plot of the delay measured in an RF Cable of 550m in length. The delay has been fitted to a transfer function as explained above

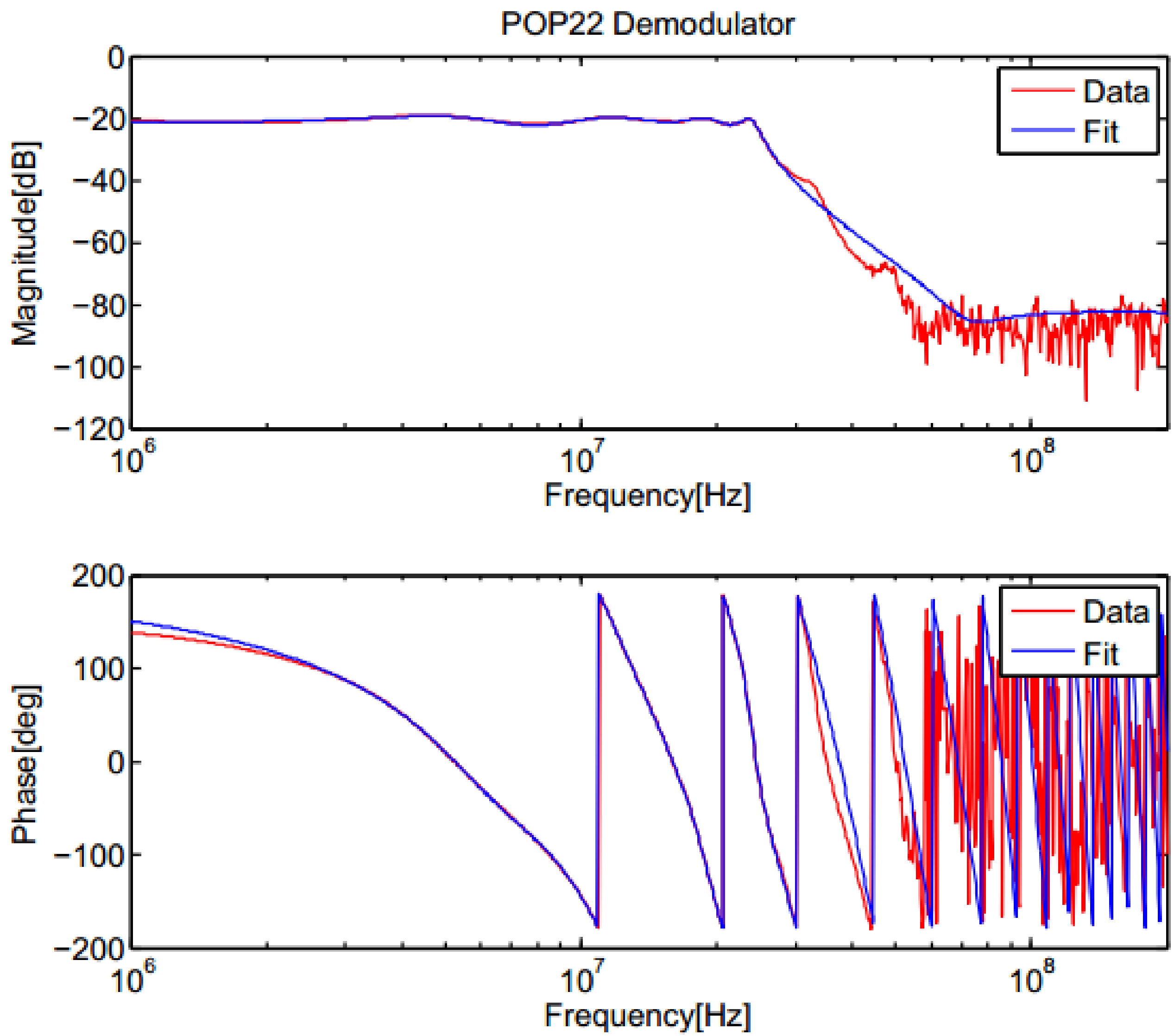

Figure 5: Plot of attenuation caused by a demodulator board. The attenuation has been fit into a transfer function model using vector fitting.

8 Usage Guide

The PDFR system has been documented in the 40m wiki and all the relevant information about making changes and keeping it updated have been mentioned :

1. https://wiki-40m.ligo.caltech.edu/Electronics/PDFR_system

9 References

1. Alexander Cole, 2013, LIGO-T1300618-v3 Automated Photodiode Frequency Response Measurement System

2. Barry Barish and Rainer Weiss,1999, LIGO and the detection of gravitational waves,*Physics Today*

3. Alexander Cole's wiki page :https://wiki.ligo.caltech.edu/ajw?AlexanderCole

4. B. Gustavsen and A. Semlyen, "Rational approximation of frequency domain responses by Vector Fitting", IEEE Trans. Power Delivery, vol. 14, no. 3, pp. 1052-1061, July 1999.

10 Acknowledgments

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