

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY  
- LIGO -  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

<b>Technical Note</b>	<b>LIGO-T1300618-v3</b>	2013/09/27
<b>Automated Photodiode Frequency Response Measurement System</b>		
Alexander Cole Mentor: Eric Gustafson		

**California Institute of Technology**  
**LIGO Project, MS 18-34**  
**Pasadena, CA 91125**  
Phone (626) 395-2129  
Fax (626) 304-9834  
E-mail: info@ligo.caltech.edu

**Massachusetts Institute of Technology**  
**LIGO Project, Room NW17-161**  
**Cambridge, MA 02139**  
Phone (617) 253-4824  
Fax (617) 253-7014  
E-mail: info@ligo.mit.edu

**LIGO Hanford Observatory**  
**Route 10, Mile Marker 2**  
**Richland, WA 99352**  
Phone (509) 372-8106  
Fax (509) 372-8137  
E-mail: info@ligo.caltech.edu

**LIGO Livingston Observatory**  
**19100 LIGO Lane**  
**Livingston, LA 70754**  
Phone (225) 686-3100  
Fax (225) 686-7189  
E-mail: info@ligo.caltech.edu

Figure 1: Schematic optical configuration of 40m interferometer at Caltech.

## 1 Introduction

LIGO will detect gravitational waves using laser interferometers that will be quantum noise limited over most of the apparatus's operating frequency range. In building an interferometric gravitational wave detector that works at the limits set by quantum mechanics, it is necessary to ensure that the detector can be controlled and read out optically. In the LIGO interferometer, several photodiodes are used to sense various degrees of freedom and provide feedback signals to position the mirrors so that the cavities maintain optical resonance. In addition, the main interferometric gravitational wave signal is read out with a photodiode.

In this sort of precision physics experiment it is necessary to treat the photodiode and its readout electronics as systems whose performances, including frequency response, can change over time and with changing operating conditions. The goal of this project is to build an automatic frequency response measurement system for the gravitational wave detector photodiodes. This system will use a modulated diode laser coupled through a fiber optic distribution system to illuminate the photodiodes and then automatically and quickly measure the frequency response of each photoreceiver using a network analyzer and an RF switch to select the photodiodes one after another. The experiment is being carried out at Caltech on the LIGO 40m prototype interferometer. We also designed this system to be scalable to Advanced LIGO standards so that the LIGO sites can adapt it to their own needs.

## 2 Schematics

## 2.1 Interferometer Layout

The optical configuration of the 40m-interferometer test bed is shown in Figure 1. It is a Dual Recycled (signal and power) Fabry-Perot Michelson (DRFPMi) Interferometer. Each arm (x,y) of the interferometer consists of two mirrors that form an optical cavity. The mirror near the beam splitter (BS) is called an input test mass (ITM<sub>x,y</sub>) while the second mirror, placed at a distance of 38m from the ITM, is called end test mass (ETM<sub>x,y</sub>). To increase the power inside the arm, a partially reflecting mirror called the power-recycling mirror (PRM) is installed at the symmetric (bright) port of the interferometer to recycle the light back into the interferometer. To increase sensitivity to the gravitational wave signal, a partially reflecting mirror is also installed at the anti-symmetric (dark) port of the interferometer. This mirror is called a signal-recycling mirror (SRM). The recycling cavities are folded using folding mirrors (PR2-PR3, SR2-SR3) to extend the lengths of the recycling cavities while allowing them to fit into the vacuum system. The power-recycling mirror is preceded by an Input Mode Cleaner (IMC), a triangular cavity used for filtering the optical mode of the input beam. Also, the mode cleaner serves as a reference cavity to stabilize the frequency of the laser. Similarly, the signal-recycling mirror is followed by an Output Mode Cleaner (OMC) cavity, which is used to filter out the higher order laser spatial modes and additional unwanted sidebands from the transmitted beam.

## 2.2 RF Photodiode Locations and Functions

In the schematic diagram of the interferometer in Figure 2 we also show the RF photodiodes used for control. The modulation frequencies  $f_1$  and  $f_2$  used in the 40 meter prototype interferometer are 11MHz and 55MHz respectively. The photodiode signals provide feedback to the various mirrors such that cavity resonances are acquired and maintained. For example, the error signal for Power Recycling Cavity (PRC) length control is derived from REFL33 and REFL165 or from POX11 and the feedback goes to the power recycling mirror. For the Signal Recycling Cavity (SRC) length control REFL165 and REFL55 provide the necessary error signals and similarly for other degrees of freedom.

# 3 Photodiode Measurement

## 3.1 Single Diode Measurement

We begin by reviewing the basic principle of a transfer function of frequency response measurement for a single photodiode. Figure 3 shows a single PD under test that is illuminated by the output of a diode laser. The output power of the laser is amplitude modulated by the drive current into the diode laser. This drive current modulation is provided by the RF output of the Network Analyzer (NA) The NA produces a swept sine wave over a range of preset measurement frequencies and at each measurement frequency the NA measures the amplitude and phase response of the output of the PD under test. In this experimental setup the output of the PD under test is compared

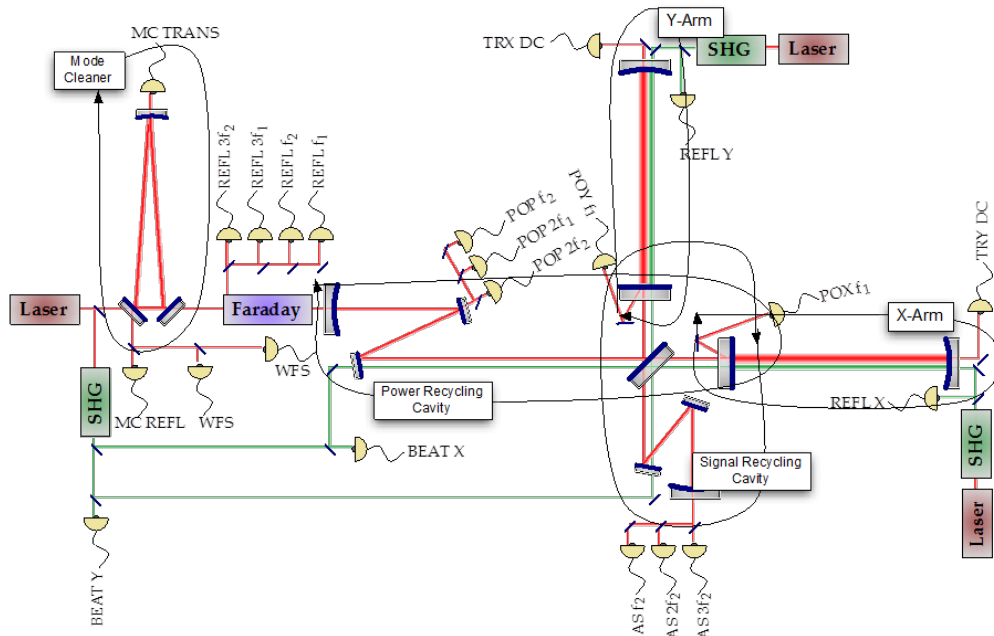


Figure 2: Schematic diagram of the interferometer with various RF photodiode locations. Some photodiode outputs provide feedback signals that are used to ensure cavity resonances which are vital to the operation of the interferometer. Other photodiodes are used to sense various degrees of freedom. Additionally, the main interferometric gravitational wave signal is measured with a photodiode. The goal of this project is to implement a system to automatically measure frequency response for each photodiode in the interferometer.

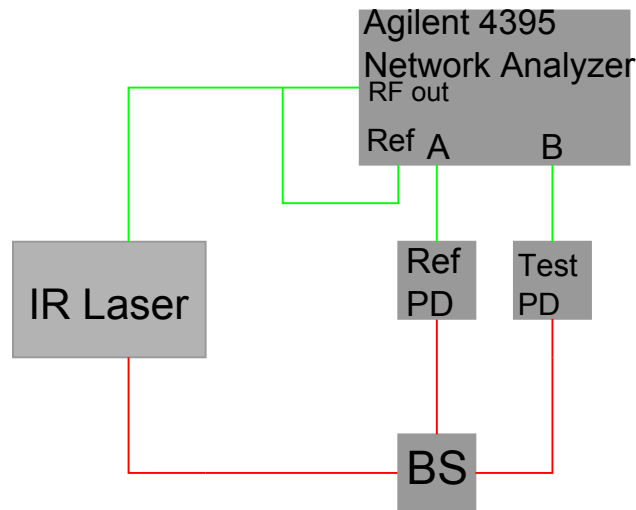


Figure 3: Single photodiode transimpedance measurement. The Agilent Network Analyzer's RF output sends a sine wave swept over a range of frequencies to the laser. The output of the laser is sent to both the reference photodiode and the test photodiode, which are fed into the inputs of the Network Analyzer. The Network Analyzer can be set to compare either photodiode's output with the Network Analyzer's RF output or with the other photodiode. This generates an experimental transfer function for the test photodiode.

General Schematic for Photodetector  
Frequency Response Measurement  
DCC: D1300603

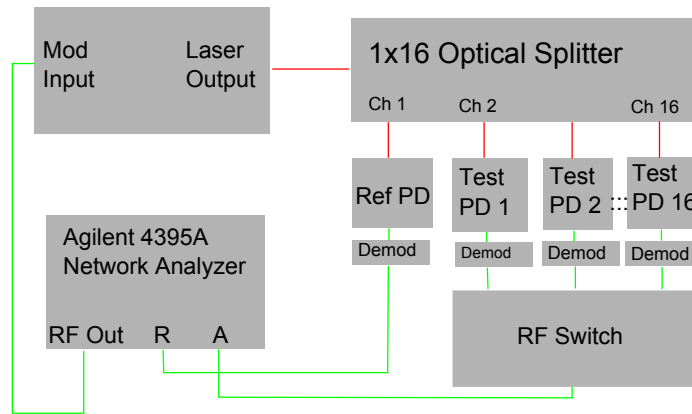


Figure 4: Schematic diagram for measuring the transfer functions of a collection of photodiodes. The general idea is the same as in Figure 3; however, in this setup, a 1x16 Optical Splitter distributes the laser's output among all the photodiodes. The demodulation boards at each photodiode's output are of primary use for aspects of the interferometer outside the scope of this project, but they may affect our measurements in ways yet to be determined. The RF switch then chooses which photodiode's output to send to the Network Analyzer for analysis. This process is performed multiple times, with each test photodiode having its output sent to the Network Analyzer once.

to a known reference PD to make sure that any variations in laser output power are normalized out. In this way the transfer function of frequency response of the PD under test is measured.

### 3.2 Transimpedance Measurement for a Collection of Photodiodes

Again a diode laser is used to provide an amplitude modulated signal to illuminate the PDs. However, this time the diode laser output power is divided using a 1x16 Optical Splitter and each of the output fibers is routed to a unique photodiode. The transfer function of the PDs is again measured using a network analyzer (Agilent 4395A). The output of the PDs will be fed to the network analyzer using a 16x1 RF switch. This will allow us to select each photodiode individually and feed the signal into the network analyzer. An ILX LDC 3744C diode laser controller will be used to provide the DC current to the diode laser and to control the diode laser temperature using a thermoelectric cooler. Using this experimental setup we will be able to measure all of the photodiodes one at a time using only one diode laser.

## 4 Subsystems

## **4.1 Network Analyzer**

We use an Agilent 4395A Network Analyzer (NA) in our system. Communication with our NA was performed via GPIB over a local wireless connection.

## **4.2 Diode Laser**

Our diode laser module has a modulation input that takes an RF signal and uses it to modulate the amplitude of the laser's output at the input frequency. We use a fiber-coupled output to distribute our laser light to the optical splitter.

## **4.3 1x16 Fiber Splitter**

Our 1x16 non-polarization-maintaining fiber splitter takes the output of the laser and sends it to several fibers. Each fiber delivers laser output to a photodetector via a launcher mounted on an optical table with the detector.

## **4.4 RF Switch**

Our RF switch is used to choose which photodetector's output will be analyzed by the NA. We communicate with the switch via TCP/IP.

## **4.5 Fibers and Cables**

Our system required the running of many fibers and cables. We used kevlar tubes to protect the fibers and assembled the cables ourselves due to the need for custom lengths. The cables were used to carry our RF signals. We used a spool of RG405 and connectorized them with SMA ends.

# **5 Completed Work**

## **5.1 Documentation**

One of our main goals was easy implementation at the sites. In addition to factoring in physical and design needs, we sought to be exhaustive with our documentation so it will be easy to recreate our

system. The RF photoreceivers, Diode Laser Module, and 1x16 Optical Splitter have been extensively documented. We have compiled manufacturer schematics, taken pictures, and made drawings of the relevant aspects of these components. Links to the LIGO DCC pages for these can be found in the "Documents" section of <https://wiki.ligo.caltech.edu/ajw?AlexanderCole>.

## 5.2 Mechanical

The 1x16 Optical Splitter, RF Switch, Diode Laser Module, and Laser Power Supply were mounted at the 40 meter interferometer in various racks. The laser's fiber has been connected to the optical splitter such that its output goes to all of the photodetectors being considered. All of the photodetectors under consideration have launchers sending laser light distributed from the 1x16 Optical Splitter to their inputs.

## 5.3 Automation and Analysis

To automate the collection and plotting of data in the 40 meter interferometer, we use a GPIB (General Purpose Interface Bus) to communicate with the NA from the control room. Located in `/opt/rtcds/caltech/c1/scripts/general/netgpipdata` are several useful scripts for this process. `./NWAG4395A -s startFrequency -e endFrequency -c chunkSize -f fileStem -d directoryForData -m Mode (AR=A/R, etc.) -i 192.168.113.108 -g 10` runs a scan on the AG4395 NA and downloads the results as `.dat` files. These files can be interpreted to generate Bode plots using the MATLAB script `plotstuff.m`, located in `/users/alex.cole`.

We have also figured out how to use `vectfit4.m` to fit transfer function data. To be especially effective, it is important to have a good model for these functions.

## 5.4 Measurement

As an intermediate step, we used the scripts previously described to automate data collection from the NA with a bandpass filter.

Additionally, we characterized a new modification to a photodiode, BBPD MOD for REFL165. This was done locally. The schematic for our measurement is similar to Figure 3, except a beam-splitter (BS) was used to split the output of the laser between the two photodetectors. First, we calibrated the NA to account for differences in cable features between Ref PD and Test PD connections. This fixed an issue with apparent phase difference at high input frequency. This was done using the NA's `Cal` softkey.

Then we performed transimpedance measurements for the Test PD and Ref PD relative to the RF output of the NA and relative to each other.

Next, we made DC measurements of the outputs of the photodetectors to estimate the photocurrent distribution of the transimpedance setup. These DC measurements were performed with the laser at a constant power and the outputs of the photodetectors being sent to a multimeter. By photocurrent distribution, we mean how the beamsplitter, respective quantum efficiencies, generalized impedance, and other features of the photodetectors influence how much current flows through each detector with a DC input.

Finally, we measure the output noise as a function of photocurrent. We used white light from a light bulb at constant voltage, with the photodetector output being sent to the NA. Input voltages for the light bulb ranged from 0 mV to 6 V. Data was downloaded from the NA using `netgpibdata` from the `scripts` directory.

We also used the Network Analyzer, Laser Diode Module, and 1x16 Optical Splitter fiber distribution to perform transimpedance measurements for several photodiodes. Using the `NWAG4394A` script, we had the Network Analyzer's RF output sweep from 1MHz to 500MHz. This output went to the modulation input of our diode laser, which had its output sent to all connected photodetectors (including the Test PD and Ref PD) via our 1x16 Optical Splitter fiber distribution system. The Network Analyzer divided the Test PD's output by the Ref Det's output to account for variation in laser output power and sent transfer function data back to the control room computer. In Figure 9 we present the data retrieved by this procedure for POX11. The data was then fitted using `fit.m`, a script that utilizes `vectfit4.m` and focuses on regions of interest specific to each photodetector.

## 5.5 Automation and Analysis

We use TCP/IP to communicate with the switch. The general programming flow for our "master script" is:

Run `NWAG4395A` to collect data from first photodetector (specify frequency range with command line options) (name the data file using `bash date/time/photodetector name`).

Use TCP/IP to tell RF switch to move on to the next photodetector.

Repeat until data has been taken from all photodetectors.

Plot data , save figures to file, use `vectfit4` to fit data and compare with canonical set.

Each data set outputs two plots (which are also saved to file). One compares the new data with the canonical set's data and one shows the transimpedance fit. Both figures focus on regions of interest particular to each photodetector.



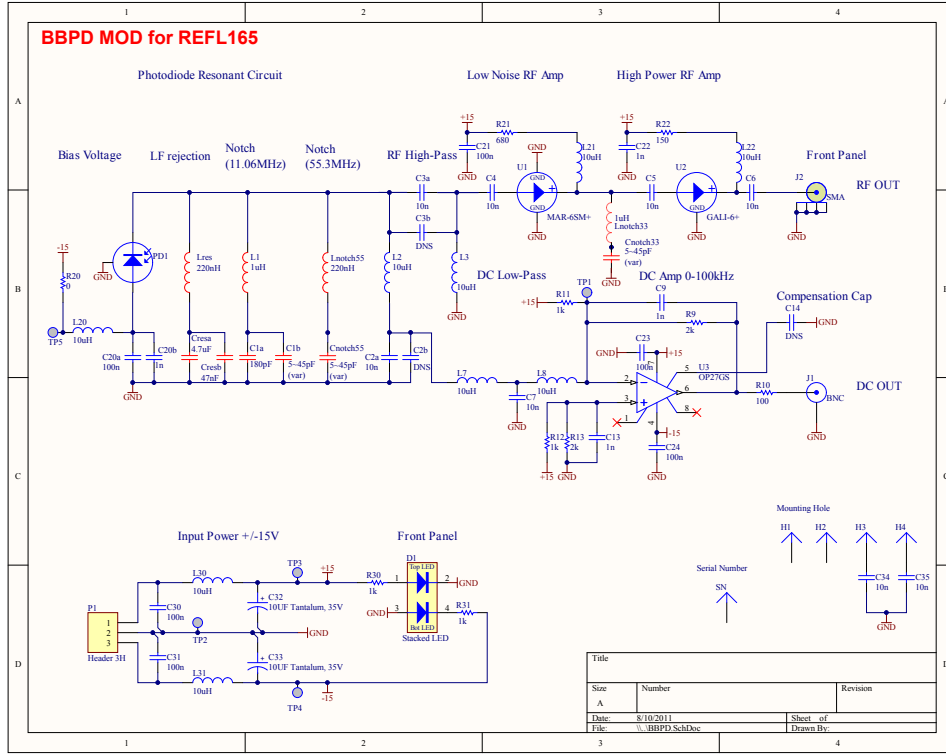


Figure 5: The BBPD MOD for REFL165 that we characterized.

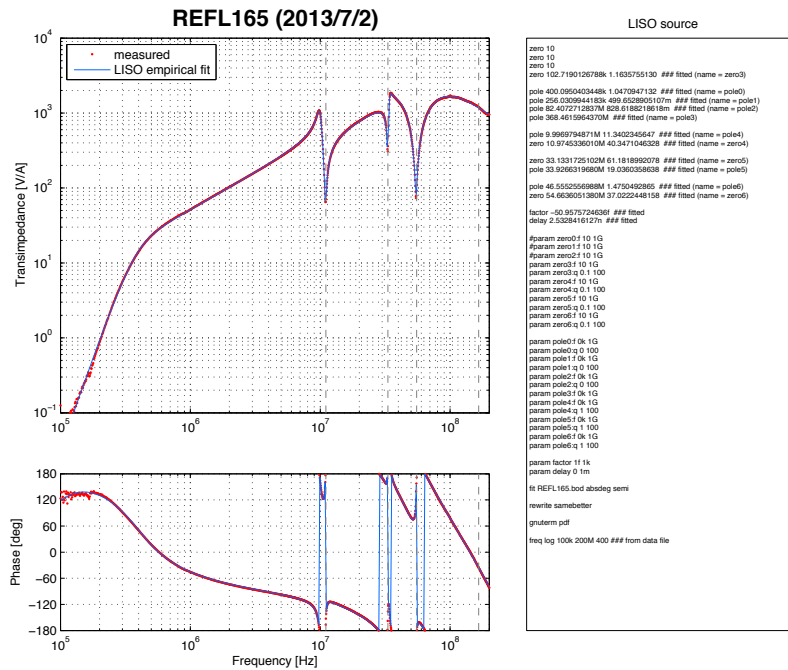


Figure 6: The transfer function for the REFL165 BBPD MOD. Data was collected locally with an amplitude modulated diode laser and an Agilent 4395A Network Analyzer.

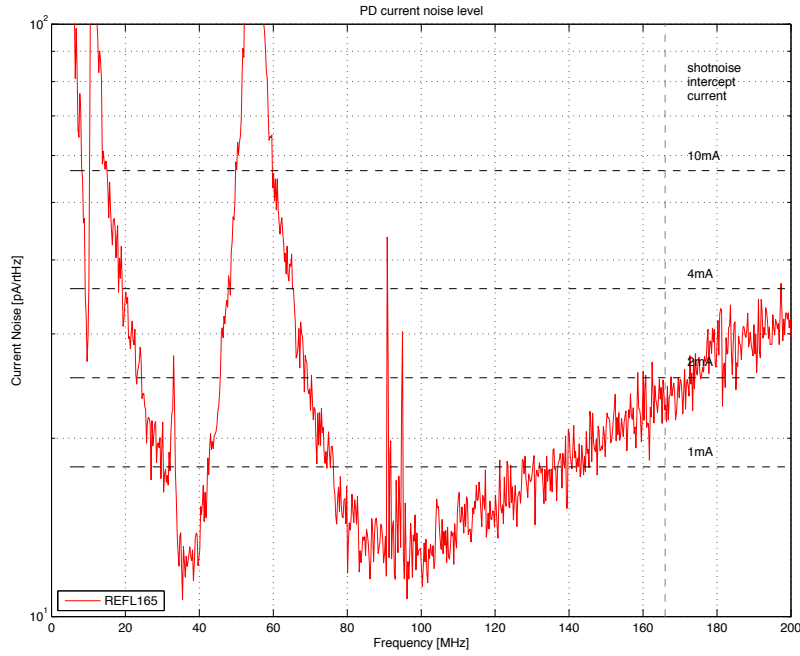


Figure 7: Current noise spectrum for the BBPD MOD for REFL 165. Data was collected locally.

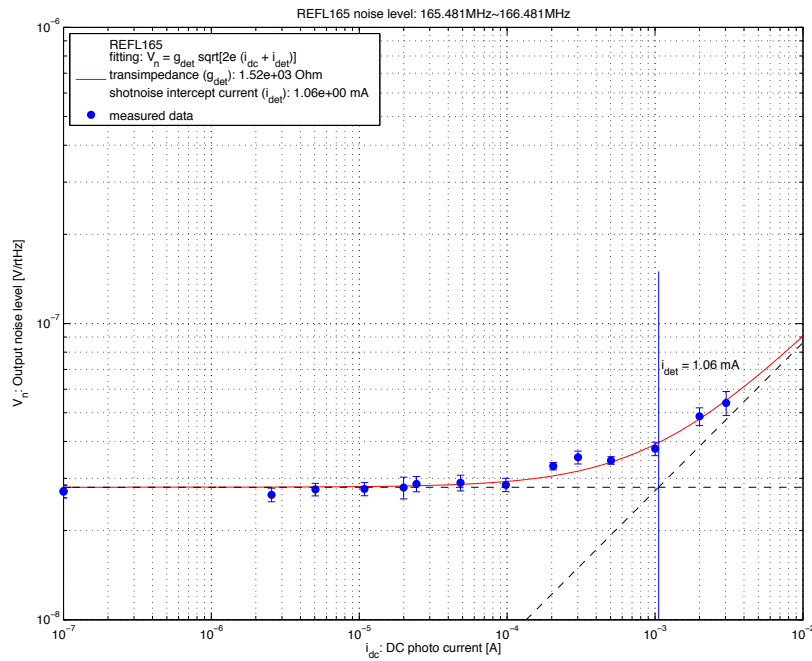


Figure 8: Shot-noise intercept current for the BBPD MOD for REFL165. Data was collected locally with white light from a light bulb and the Agilent 4395A Network Analyzer.

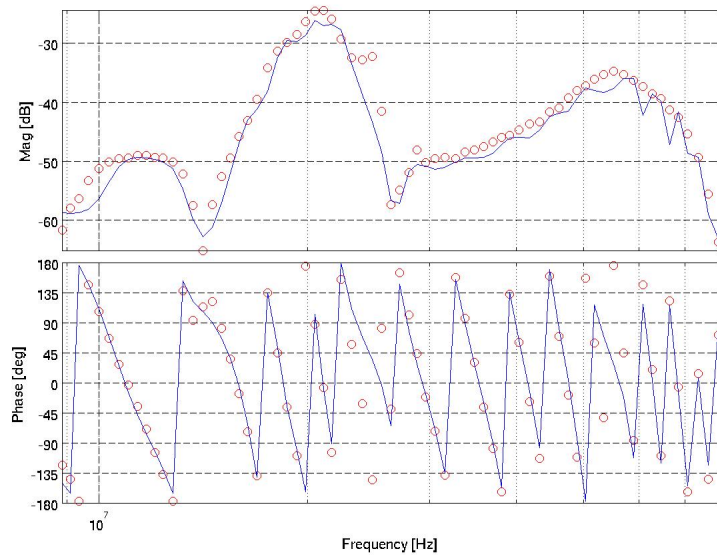


Figure 9: Transimpedance data for REFL55. The red circles represent the raw data, while the blue line is the fit as described in the "Automation and Analysis" section. Data was collected and analyzed remotely using the NWAG4395A script using our final measurement routine.

## 5.6 Investigation and Model-Building

All of the photodetectors have several poles and zeros at various frequencies. However, some of these are removed by filters in the demodulator boards. We measured the transfer functions for the filters between the input and RF MON output using our standard NA procedure. Transfer functions for our filters show that all poles and zeros are washed out except for the frequency given in a particular photodetector's name. For example, the only pole we can find for REFL55 is at 55 MHz; the signal to noise ratio is too low for other poles.

## 5.7 Usage Guide

This subsection describes how to operate the previously described implementation at the Caltech 40 meter prototype interferometer.

On the mechanical side, turn on:

- Diode laser (in rack 1Y1)
- RF Switch (in rack 1Y1)
- Reference PD (under the POY table)
- AG4395A Network Analyzer (on mobile cart)

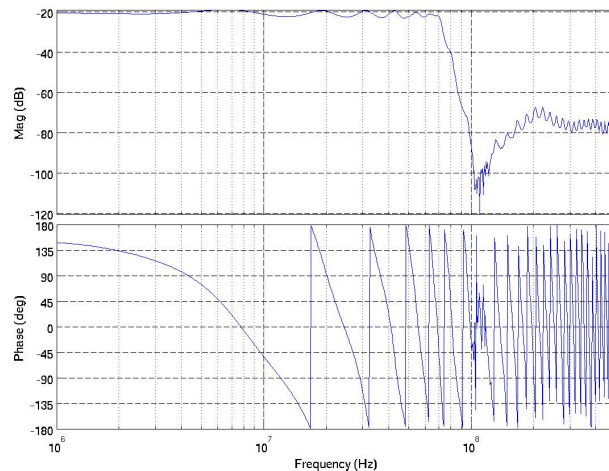


Figure 10: Transfer function for the filters in the REFL55 demodulation board in between the input and "RF MON" output. The frequency response for the filter means that the poles for REFL55 that are at frequencies higher than 55MHz will get washed out.

The NAs RF output should go to the lasers modulation input, the reference PDs output should go to the NAs R input, and the RF Switch chassis output (which is the combination of the two switches COM channels using a splitter) should go to the NAs A input.

Once this is done, navigate into /users/alex.cole and run PDFR.sh. This script collects data for each photodetector under consideration by switching using a python script and communicating with the NA via GPIB. It then sends all the data to RF.m, which fits the functions, plots the latest data against canonical data, and saves the plots to file.

The fitting function, fit.m, also outputs peak frequency to the command line. This function uses PD name data (e.g. REFL33) to choose an interval with minimal noise to fit.

The main script prompts the user to press enter after each NA sweep to make sure that measurements dont get interrupted/put out of order by RF switching. Once you're done, you should turn off the laser, NA, RF Switch, and reference PD.

### 5.7.1 Troubleshooting

Sometimes, the NA refuses to perform a particular sweep. If this happens, it is beneficial to keep the matlab script from trying to analyze this PDs data. Do this by opening up RF.m and commenting out the calls to fit and canonical for that PD.

If fit.m rejects a particular set of data, it is often the case that the N/P ratio (where N is order of approximation and P is number of points in the interval) is too high. You can fix this by reducing N or making the PDs frequency range (chosen in the fnew-idx line) larger.

## 5.7.2 Choosing a Single Photodetector

If you only want to collect transimpedance data for one PD, first look up which switch input it belongs to. This information is contained in `/users/alex.cole/switchList`. To turn the switch to a particular input, use a command analogous to:

```
python rf.py ch7
```

This command uses TCP/IP to tell the switch to look at channel 7. Switch input numbers range from 1 to 16, though not all of them are in use.

Once the switch is looking at the correct input, you can run a sweep and download the data by typing `/opt/rtdcs/caltech/c1/scripts/general/netgpibdata/NWAG4395A -s 1000000 -e 500000000 -c 499000000 -f [filestem for output] -d [path of directory for output] -i 192.168.113.10 -g 10 -x 15`.

# 6 Future Work

## 6.1 Baluns Chassis

In our final setup, we will have the output of each photodetector go through a balun before being input to the switch. The panels for the box containing the baluns have been ordered. The baluns have yet to be ordered. A drawing of the baluns box can be found with the documentation previously described.

# 7 Acknowledgments

Eric Gustafson served as a wonderful mentor for this project. My REU was funded by the National Science Foundation and hosted by LIGO at Caltech.