Development of a Mach–Zehnder interferometer to improve the small torsion pendulum angular readout on the 1TM pendulum

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ABSTRACT

I report on the current progress towards the development of a Mach–Zehnder heterodyne wavefront sensing interferometer to improve the small torsion pendulum angular readout on the 1TM (Test Mass) pendulum and discuss my role in the project. The interferometer is being developed on an optical bench, and it's a project that I was given the task to start from the beginning with the help of Dr. William J. Weber.

Introduction

The Trento group responsible of testing the TM for the upcoming space missions LISA Pathfinder, and LISA, has come to the conclusion that to better understand the noise interacting with the TM a better angular readout needs to be achieved. The use of a Silica fiber, replacing Tungsten, has shown an improvement in reducing the torque noise floor below that allowed by tungsten. In addition to a number of possible true torque noise sources, current measurements are limited by the noise in the readouts, autocollimator and gravitational reference sensor (GRS), used to measure the pendulum angular deflection. Neither is able to resolve the fused silica thermal noise floor. While the excess torque noise can be identified with the averaged cross-spectrum data analysis technique, readout noise adds uncertainty to the estimates and complicates any debugging of true force noise sources [1]. The effort has been set forth to build an interferometric angular readout with a sensitivity near the desired goal of 5nrad/sqrt(Hz). Having the interferometric angular readout does not guarantee reaching the limits of the fused silica thermal noise floor, but it is a necessary step to being able to identify sources of excess force noise [2].

Personal Contribution

Upon being briefed of the task of putting together a Mach–Zehnder interferometer I was given the job, to get me acquainted with some of the components that I would be using in the process of building the interferometer, to build a unity gain phase shifter to test the code that Daniele had written to measure any shifts in the phase of a signal. This way we could intentionally shift the phase of the signal and detect if the code was doing what it was supposed to do.

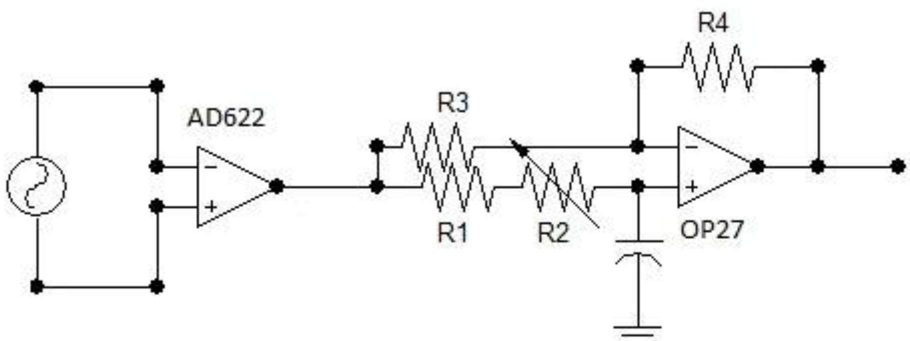

Fig. 1 Unity gain phase shifter schematic.
R1-1000, R3&R4-13.7k, R2-100k Ohm Potentiometer

Fig. 1 shows the schematic of the unity gain phase shifter and it comprises of an AD622 instrumentation amplifier, OP27 precision operational amplifier, 16nF capacitor, and resistors. The use of the instrumentation amplifier is to not introduce any noise from the function generator as the input signal goes into the operational amplifier.

After building this on the bread board and once tested with Daniele's code I assembled this in a small box that could be used continuously without having to build and take apart on a bread board after each use. Putting together this unity gain phase shifter was a great exercise to prepare for the more complex assembling that would require the building of the interferometer.

With the unity gain phase shifter completed the next step was to characterize all the components of the interferometer. The first instrument to be characterized was the Novatech Instruments Frequency Synthesizer which was in interface with the lab computer. Using the sine wave signal output from the frequency synthesizer, I tested the output peak to peak amplitude as a function of bit, voltage, which was set with the computer. Also recorded was the output RMS as a function of bit. A peak to peak reading is a measure taken from the bottom to the top of the curve and RMS is the root-mean-square.

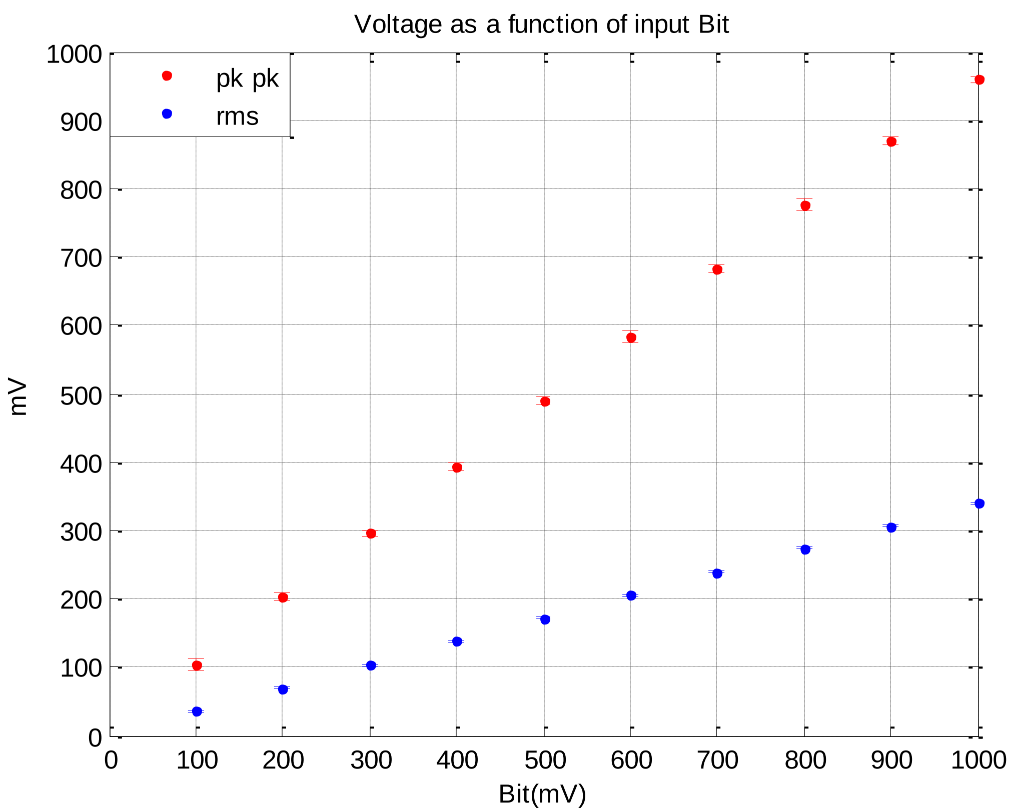

Fig. 2

Figure 2 shows how the peak to peak and rms output voltage are linear as the bit increases. Therefore for best performance we want to stay in the linear range and the data shows that working well within the range of 1000 bits it's mostly linear.

The next step was to introduce a voltage follower and a mixer. The output of the voltage follower would go into the mixer and the output from frequency synthesizer. The measure that I was interested in was the affect of the voltage follower with that of the frequency synthesizer from the output of the mixer.

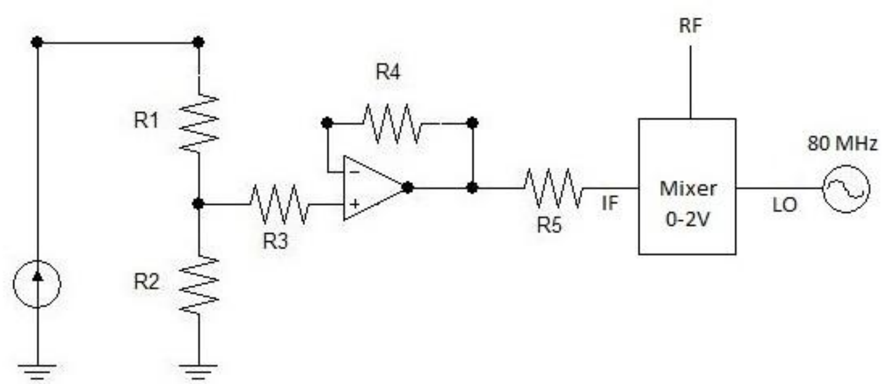

Fig. 3
R1-13.7k Ohms, R2-10k Ohm Potentiometer, R3&R4-500 Ohms, R5-56 Ohms

Fig. 3 shows the schematic setup of the introduction of the voltage follower and the mixer. The output voltage going into the follower is calculated using equation 1 where Vin is 14.55 volts.

$$Vout = \frac{R2}{R2+R1} Vin \quad \text{eq. 1}$$

In order to not have too many variables being changed at once we choose three values to set the frequency synthesizer and have the voltage follower as the only changing variable.

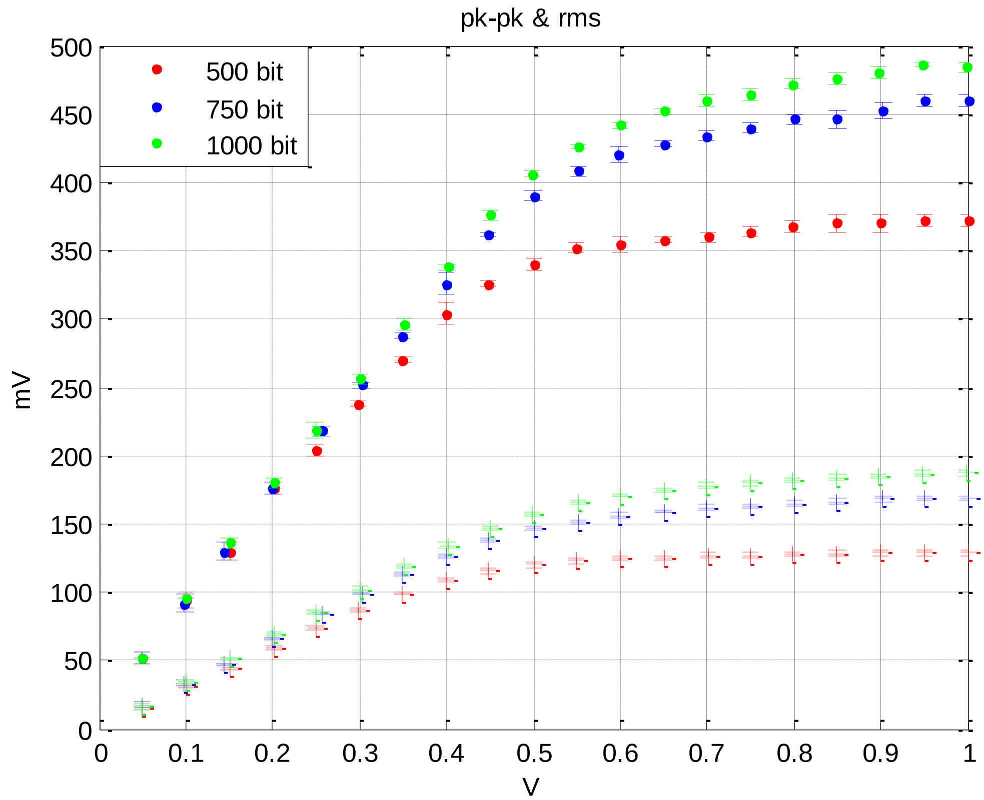

Fig. 4

Figure 4 shows how the introduction of an outside voltage into the mixer mixed with the output of the frequency synthesizer no longer stays linear like the graph of the frequency synthesizer showed. The output of the mixer only remains linear up to 400 mV input from the voltage follower. It's interesting to also note that the three different bits that were set in this experiment have a linear increase until the output of the voltage follower reaches 400 mV and then it decreases some. Both measures, the peak to peak and rms, are shown here color coded corresponding to the bit size used.

The next step in the process of characterizing the components of the interferometer is to build the loop control on the bread board that will control the amplitude of the laser.

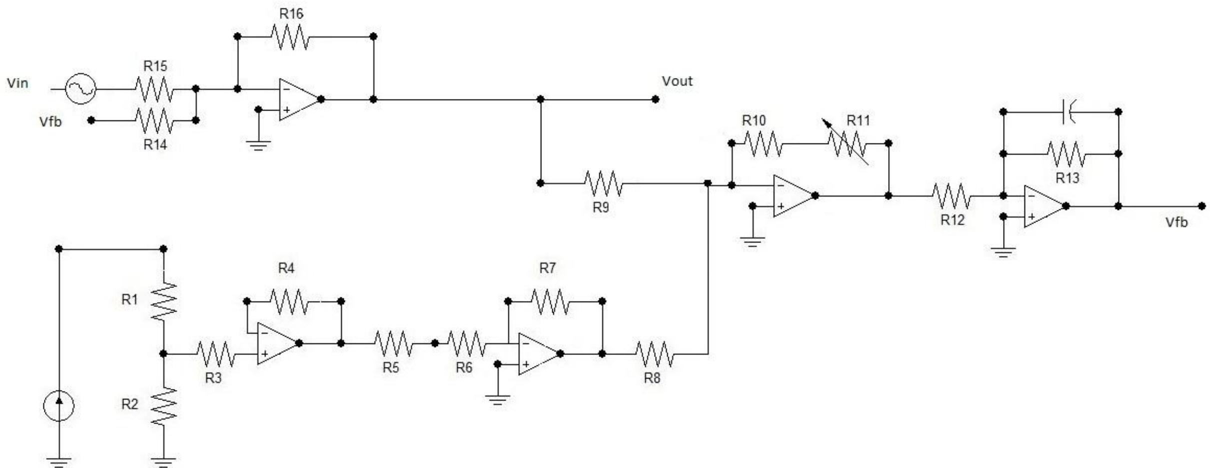

Fig. 5
R1=13.55k, R2=475.1, R3=561.7, R4=554, R5=54.6, R6=5.53k, R7=5.53k, R8=998, R9=1.05k, R10=986, R11=100k Potentiometer, R12=988, R13=5.54k, R14=552.5, R15=5.524k, R16=5.541k, 2.2nF capacitor;

Figure 5 show the circuit diagram, composed of op amps, of the loop control that will correct any fluctuations of the amplitude of the laser. This circuit was made for the most part to be manipulated to obtain as much gain as possible. The higher the gain obtained the better the result closes in on the expected result. The schematic with resistors 1-5 is the schematic of the voltage follower and the voltage can be set using equation 1. Following the voltage follower there is a voltage inverter going into the first summing amplifier. For V_{in} we used a frequency generator with an input voltage and it was summed with V_{fb} and inverted. This inverted signal goes out as the output. Some of this output is routed back in to the first summing amplifier and any difference between this and the set voltage follower will injected back into the feedback to make up for any deficiency in the input.

$$\text{Vout} = \frac{R9*R16\{R10*R13*R15*Vref - Vin*R8*R12*R14(1+iw*R13*C)\}}{R8*R15\{R9*R12*R14(1+iw*R13*C)+R10*R13*R16\}} \qquad \text{eq.2}$$

Using equation 2 we calculate the theoretical value that we should obtain with the values of resistance we so choose and compare this data with the data that we obtain using a lock-in amplifier and loop control circuit.

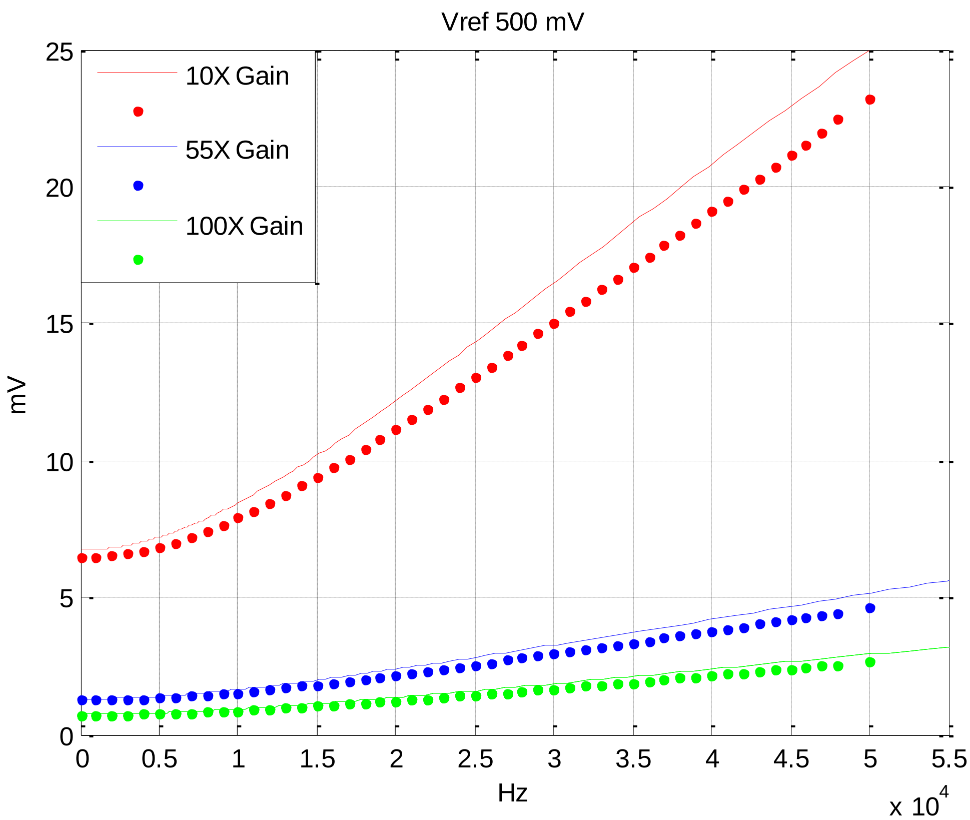

Fig. 6

Figure 6 show the theoretical calculated values, solid line, and obtained values, dotted line, analyzed by the lock-in amplifier. Notice how as the gain goes up the obtained values analyzed by the lock-in amplifier gets closer and closer to those of the theoretical values calculated. In the final circuit to be used in the interferometer we aim at having a circuit with very high gain to get very close to the desired values.

Now that we have characterized the components required to start setting up the optics, the next step is to characterize how the AOM (Acoustical Optical Modulator) affects the beam onto the photodiode. The AOM uses phonons to compress and expand periodic planes to change the index of refraction of the incoming light. In this experiment the AOM is driven by the 80 MHz frequency synthesizer.

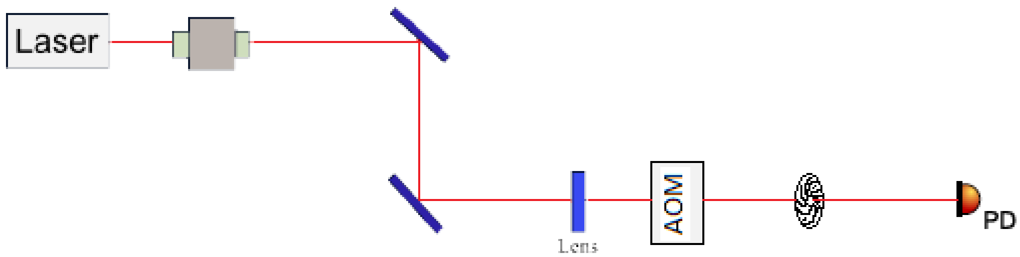

Fig. 7

Figure 7 shows the setup of the optics, AOM, aperture, and photodiode. The laser had already been characterized and was set to 600 mA to avoid overheating the surface of the photodiode.

Three measures are taken with the AOM. One measure is done with the aperture fully open allowing both the input beam and the deflected beam onto the photodiode. The second measure is taken with the aperture closed just enough to let both beams into the photodiode. The third measure only allows the deflected beam enter the aperture into the photodiode. Driving the AOM is the frequency synthesizer and the same settings that were used to characterize the frequency synthesizer are used to drive the AOM to note the change in the deflection of the output beam onto the photodiode.

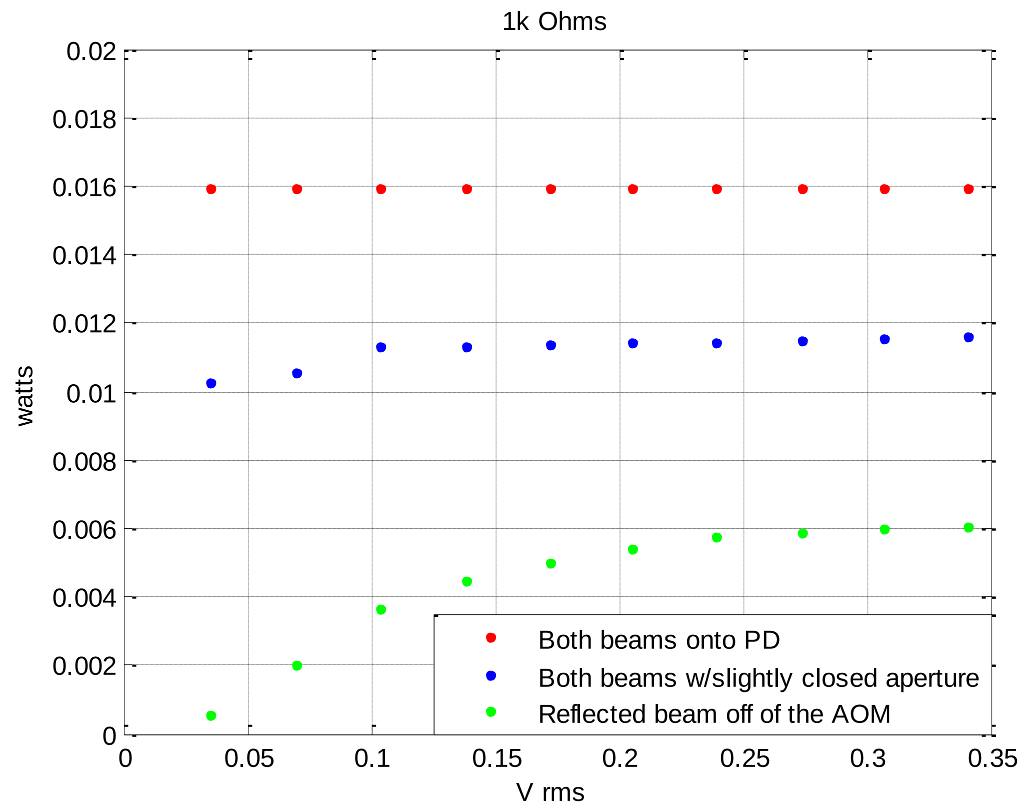

Fig. 8

Figure 8 shows the three measures made with the AOM. The data agrees with what we expected the outcome to be. With the aperture fully open, there was no change in the amount of power that went into the photodiode with respect to the change made by the frequency synthesizer, because both beams were centered for maximum resolution and any small change in the deflected beam had the same amount of exposure onto the photodiode. The test done with the aperture slightly closed to just allow both beams in, did see a slight affect due to the change made by the frequency synthesizer. There was a slight drop in power that was blocked by the aperture going in to the photodiode, but then again we expected a slight drop due to closing the aperture some because the laser beam diverges. Although the power going into the photodiode remained fairly linear after the two voltage settings, we conclude that we were letting in the two beams with fairly good resolution that the deflected beam was delivering the same amount of power after the two voltage settings to the photodiode. The measurement done only with the deflected beam going through the aperture into the photodiode did see a major correlation with what the change the frequency synthesizer was putting out. The first three voltage settings gave a linear increase, but after the third setting the curve starts to slowly decrease reaching what appears to be a limit of 6 mW. For our project we want to stay in the linear range, so that if our signal starts to drift its output remains in the linear range, and the graph tells us that working up to 100 mV is the range to work with.

With the components of the control loop characterized the next step is to put together the control loop with the laser and photodiode integrated.

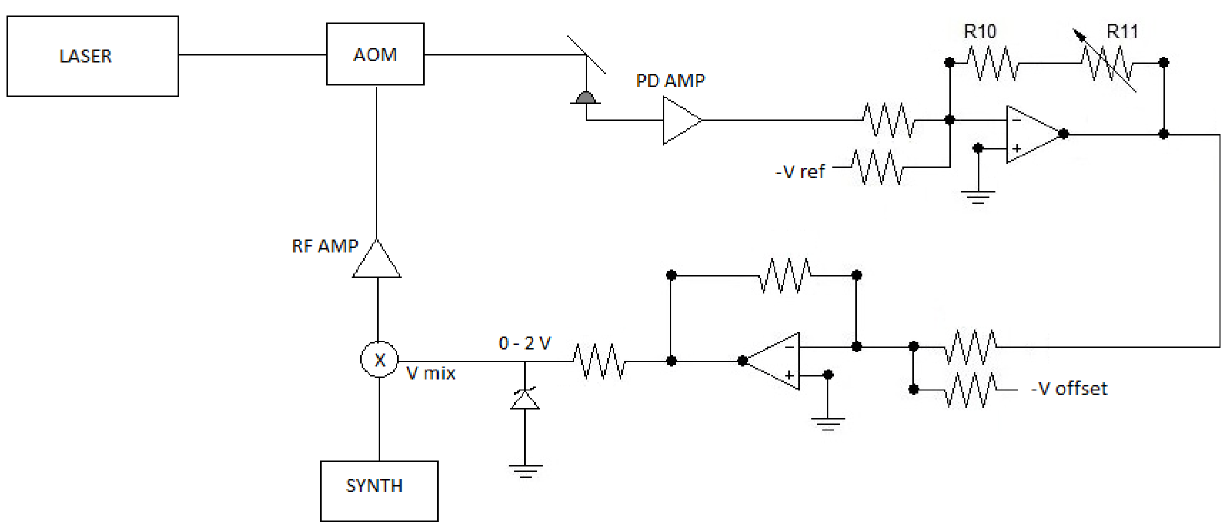

Fig. 9

Figure 9 shows the setup of the control loop integrated with the laser and the photodiode. All the resistors with exception to resistor R11 are set to 1k Ohms. R11 is a 10k ohm potentiometer. The voltage offset is held at -200 mV and the only changing variable is the reference voltage. The laser beam goes in to the AOM into the photodiode. The photodiode outputs a negative voltage; this negative voltage is summed with the voltage reference and inverted to a positive voltage reading. This positive voltage is summed with the negative offset voltage and inverted. This voltage then goes into the mixer and into the AOM to make up for any deficiency in the laser amplitude.

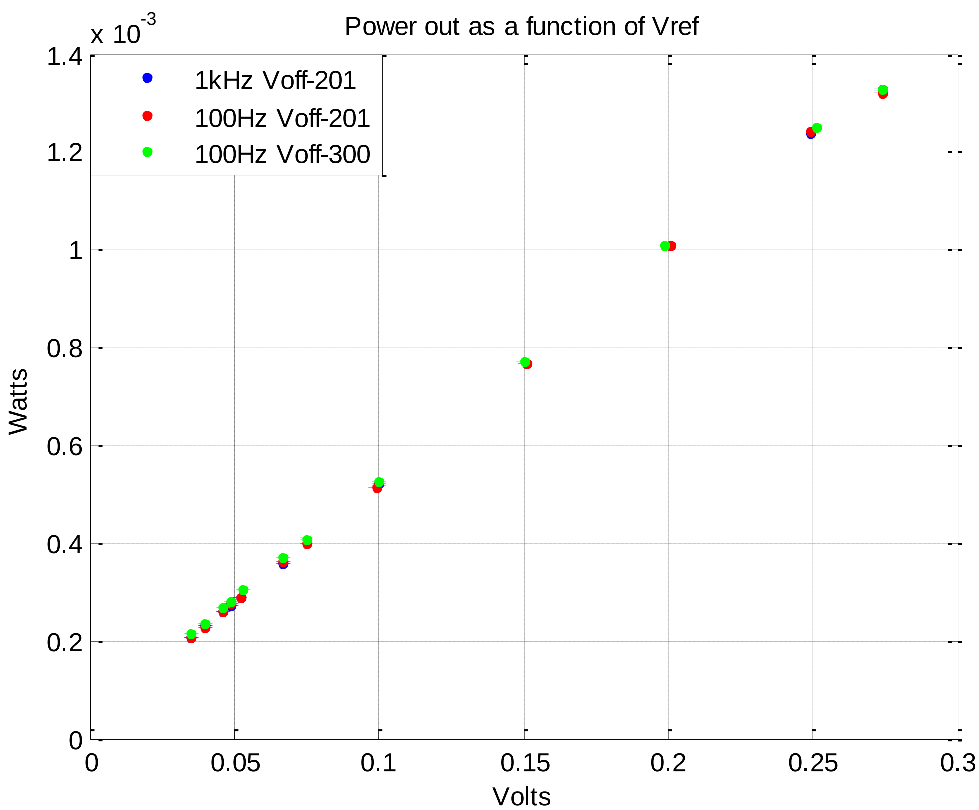

Fig. 10

Figure 10 shows the power recorded by the photodiode with the control loop. These measures were completed on the last day in the last hours of my presence being in the lab and have not yet been reproduced. Three measures were taken; one measure is done at 1k Hz with the offset voltage set to 201 mV, another measure is done at 100 Hz with the offset voltage set to 201 mV, and the last measure was done at 100 Hz with the offset voltage set to 300 mV. To calculate the power, I take the photodiode readout and subtract what the readout is with the lights on and the laser off. I then divide this voltage by the resistance and multiply this number with the photodiode power conversion factor. Using an oscilloscope we introduce a ripple in the amplitude of the laser by modulating the laser current diode by a factor of 50 mV (zero-peak). Using the reference voltage we set the measure we want and allow the control loop to make up for any deficiency in the laser power so that the measure we set is the measure the photodiode gets. If there is no deficiency in the measure then there is no correction in the amplitude of the laser. From the three measures we can conclude that changing the frequency from 1k Hz to 100 Hz, the loop control corrects the small deficiency to give what we ask from the reference voltage. Also, the change of offset voltage from 201 mV to 300 mV, again the data shows that the loop control corrects for any deficiency to put out what was asked from the reference voltage. All three measures give similar results to the others with some small error-var.

Current Progress & Outlook

My job of characterizing the components of the control loop and assembling it was a success. I assembled the control loop, showed that it worked, and left it working for Daniele to pick up and take to the next level. For the assembling of the Mach–Zehnder interferometer, it will require two control loops and the setup of the other half of the optics. Within the next few months I can see the Mach-Zehnder being assembled and tested for the integration to the 1 TM pendulum.

Acknowledgments

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