Argonne Wakefield Accelerator Laser Phase Feedback Control System

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Abstract

The Argonne Wakefield Accelerator (AWA) is a premier electron accelerator with the world's highest bunch charge to carry out fundamental accelerator research with an emphasis on Wakefield acceleration. The AWA uses an intense laser system to produce electron bunches used for various accelerator research experiments. The laser system is synchronized to a commercial laser oscillator device which operates at a 1.3 GHz Low Level Radio Frequency (LLRF). The 1.3 GHz LLRF signal is then frequency divided, and phase locked to an external 81.25 MHz reference signal using a mechanical phase shifter and a feedback control system at Argonne National Laboratory.

Because of certain limitations with the hardware used, the phase relationship between the 81.25 MHz reference signal and the 1.3 GHz LLRF reference signal is not perfectly synchronized and has the potential to drift. For this reason, a "second-stage" precision feedback control system is needed to work in conjunction with the current mechanical phase shifter to ensure that the phase drift is minimized for the AWA researchers' scientific experiments.

Introduction

The current phase shifter device used at Argonne National Laboratory (ANL) is a mechanical "trombone" like device as can be seen in Figure 1. The mechanical structure involved takes up a lot of space, has a high latency of operation, and introduces unwanted noise and vibrations into the system. Most importantly however, changes in temperature adversely effects the phase control of this style of phase shifter resulting in the phase drifting over time.

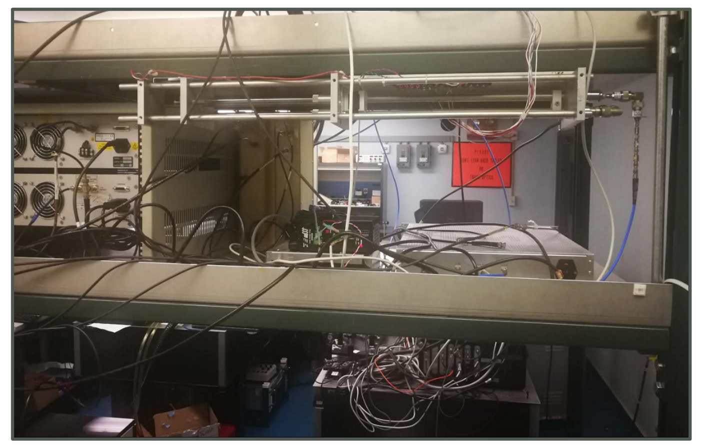


Figure 1: Mechanical "Trombone" Phase Shifter Implemented at ANL

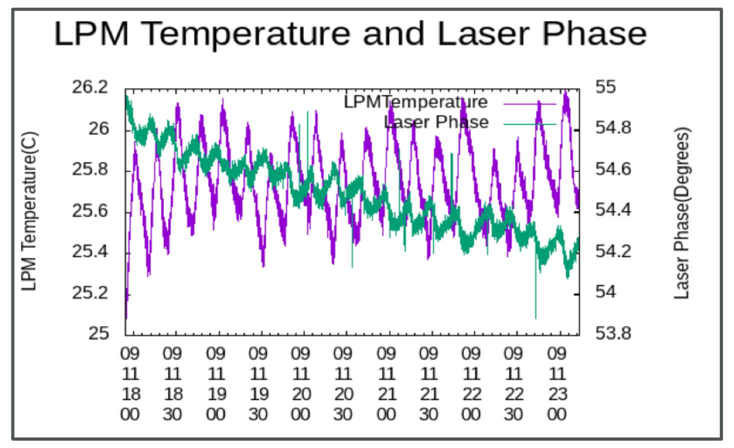
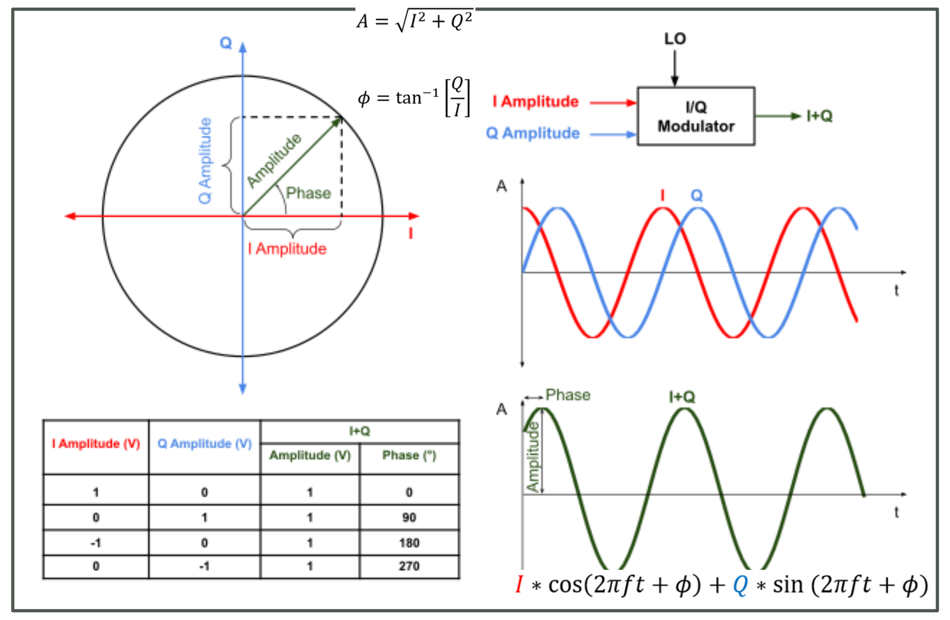


Figure 2: Laser Phase Monitor (LPM) Temperature vs Laser Phase Plot

The plot shown in Figure 2 shows a correlation between the accuracy of the mechanical phase shifter design against fluctuations in temperature within the room. While employing the mechanical phase shifter, a phase drift of roughly 1° degree per 1° C of temperature change was observed over a six-hour duration. Realizing the limitations of this mechanical phase shifter, the team determined that a "second-stage" feedback phase shifter was necessary. This extremely precise "second-stage" phase shifter design would work in conjunction with the existing mechanical phase shifter and would satisfy the 0.00625° phase shift at the 81.25 MHz frequency outlined by the ANL R&D staff. The mechanical phase shifter would be responsible for the bulk of the phase shift while the auxiliary system would offer further precise control over the phase of the 81.25 MHz frequency signal.

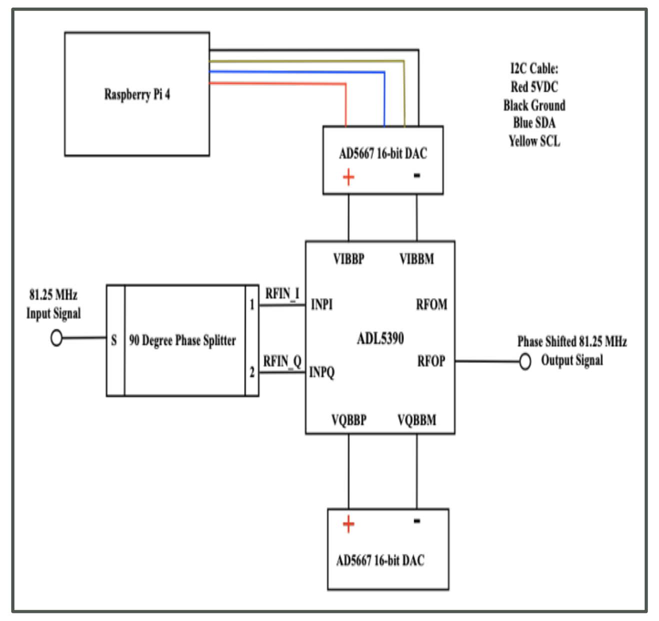
Methods and Materials

After extensive research on different methods and designs, the team chose to use the theory behind Quadrature Vector Modulation (QVM) as the focal point for the device. By using QVM a signal can be broken down into its respective quadrature components and the gain and phase can be controlled by setting the values for the I and Q components as seen below.



I Amplitude (V)	Q Amplitude (V)	I+Q Amplitude (V)	I+Q Phase (°)
1	0	1	0
0	1	1	90
-1	0	1	180
0	-1	1	270

Amplitude & Phase Modulation of I & Q Components



Functional Block Diagram of Laser Phase Feedback Control System

The key components used in the laser phase feedback control system include:

- The ADL5390 RF/IF Quadrature Vector Multiplier, which performs the actual function of phase shifting the 81.25 MHz RF signal to a user defined level
- The AD5667 16-Bit DAC, used to apply a discrete DC voltage value to the I and Q input components to shift the phase of the 81.25 MHz RF signal.
- The Raspberry Pi 4 Model B (or Arduino Nano), which is the brains of the device that handles all the processing required for transmitting and receiving data to the slave device (AD5667 16-Bit DAC).
- The Mini-Circuits ZMSCQ-2-90 Power Splitter which bifurcates the 81.25 MHz RF input signal into two equal but separate 81.25 MHz RF signals.

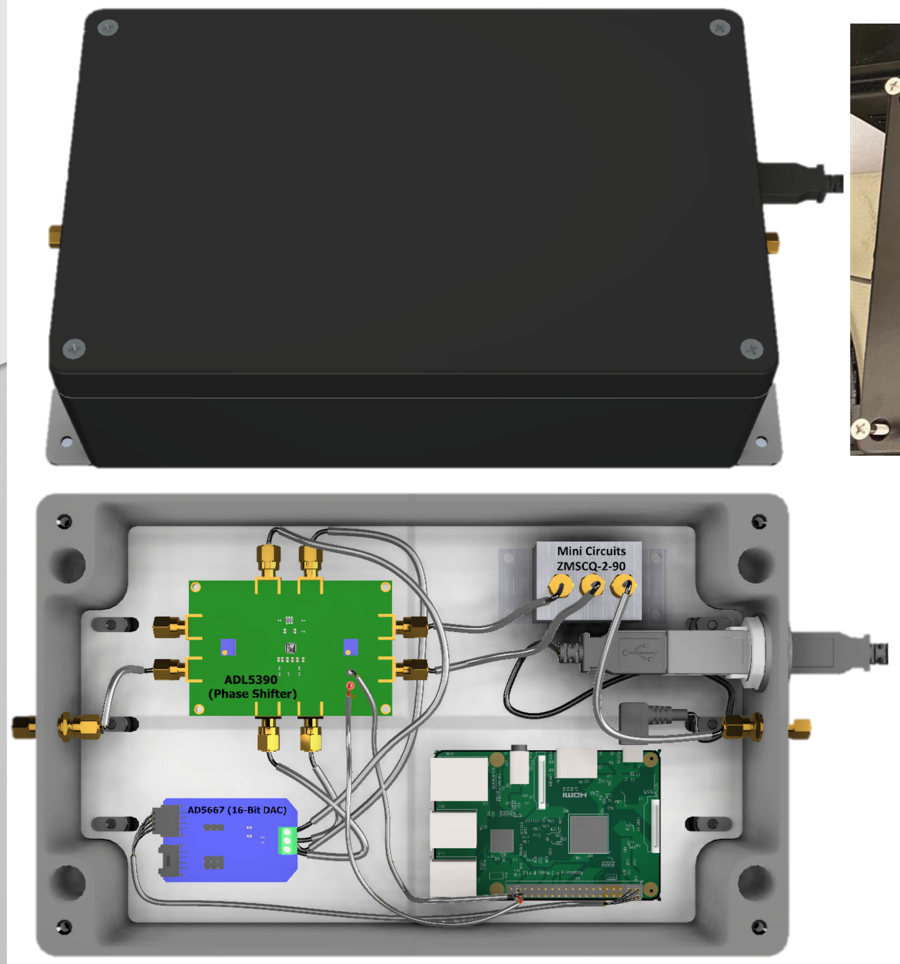


Figure 3: CAD Models of the AWA Phase Shifter

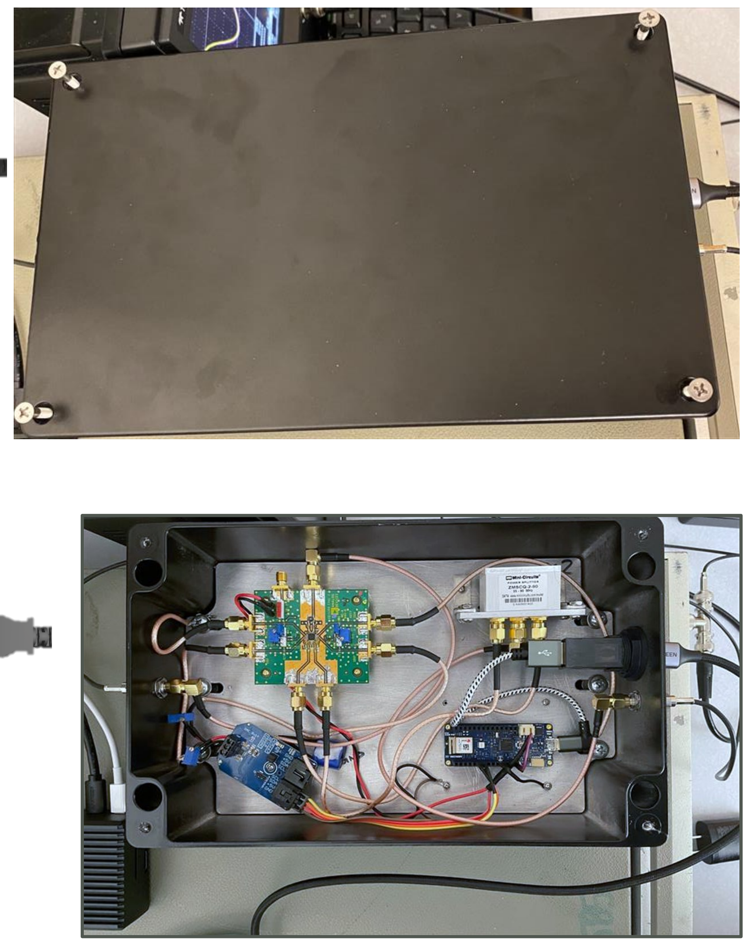
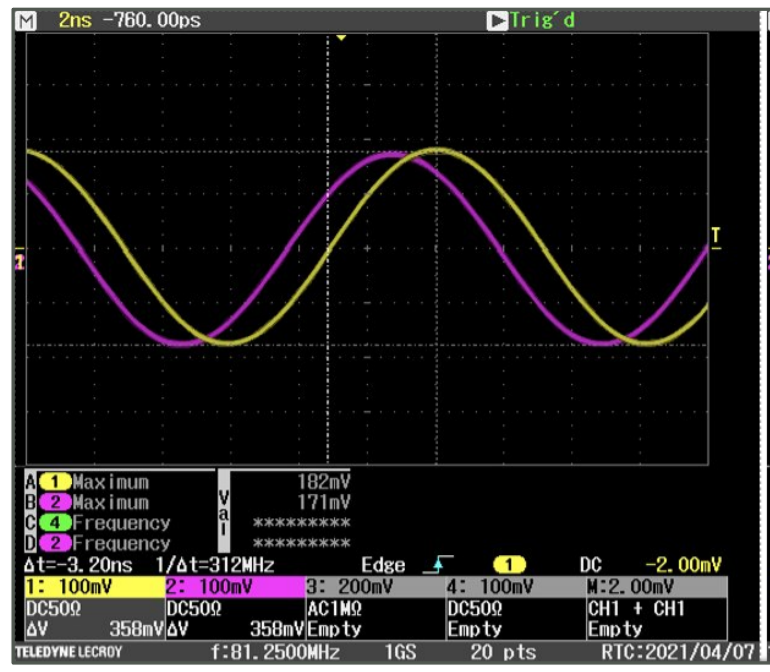


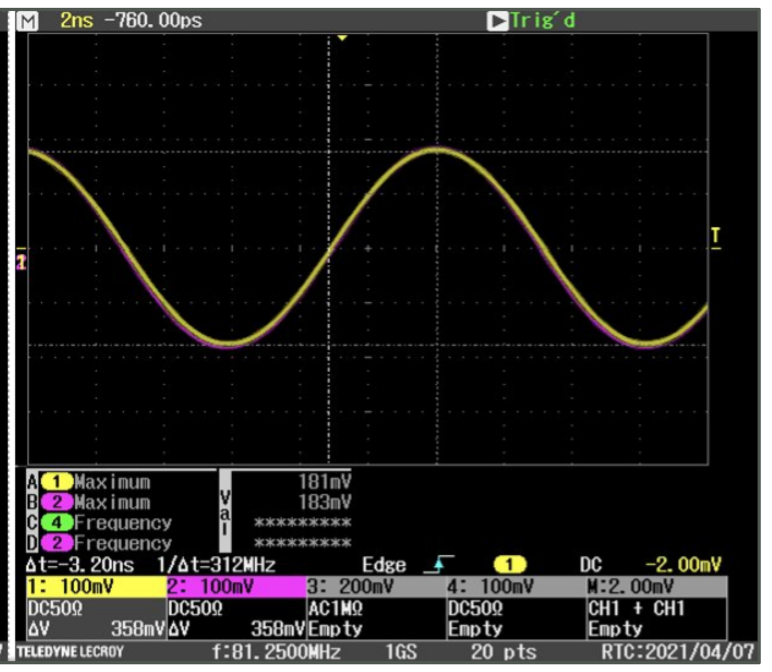
Figure 4: Realized AWA Phase Shifter

Results

After weeks of comprehensive testing, the results of the Laser Phase Feedback Control System design was determined. At an operating Frequency of 81.25 MHz the theoretical resolution that can be achieved with this device was calculated to be 0.000437° degrees at 81.25 MHz (or 0.006992° degrees at the 1.3 GHz LLRF). The device has a phase control range of ±45 degrees at 81.25 MHz. Finally, the stability of the phase meets or exceeds the targeted < 0.1° degree per 1° C temperature change due to the control system being capable of dynamically applying corrective measures to adjust the phase shift based on temperature fluctuations.



Two signals with a 45-degree phase difference



Phase Corrected Alignment

Conclusions

The team employed a Raspberry Pi 4 Model B, the AD5667 high-resolution 16-bit Digital to Analog converter, the ADL5390 RF/IF Quadrature Vector Modulator, and a Mini-Circuits ZMSCQ-2-90 hybrid power splitter to build the prototype. Based on the outcome of the results, the team was able to successfully design a product using these components which achieves the project requirements defined by the Argonne Wakefield Accelerator researchers.

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