

**PHASED ARRAY, INTEGRATED OPTICAL BEAM STEERING DEVICE
WITH THERMO-OPTICAL HEATERS**

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Phased Array, Integrated Optical Beam Steering Device with Thermo-Optical Heaters

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In this paper we demonstrate a phased array integrated optical beam steering device for sensing and analyze the efficiency of using thermo optic heaters to manipulate the phase of the signal in each waveguide to produce a steering effect in the far field. The designed silicon nitride waveguide array has eight arms that must be controlled individually. Manufacturing variations cause the fabricated device performance to deviate from the nominal design behavior. An algorithm was formulated to attain the optimal phases for each arm to steer the beam, the algorithm performed as expected but significant amount of drift appears in the output, potentially due to the temperature gradient presented on each channel. A temperature stabilization system was attached to the chip to minimize the drift, and to better characterize the behavior of the beam we including an IR camera to view the near and far fields. The algorithm proved effective by improving the intensity of the main beam, and steering the beam to our target location.

DEDICATION

This work is dedicated to my advisor, my father, my mother, and my friends for their support through out the process.

ACKNOWLEDGEMENTS

I want to thank Dr. Christi Madsen, Seeley Pentecost, Dwayne Macik, and Steven Laxton for their guidance and encouragement throughout the completion of the program.

NOMENCLATURE

Si ₃ N ₄	Silicon nitride
MZI	Mach-Zehnder interferometer
PWM	Pulse width modulation
OPA	Optical Phased Array
IR	Infrared
TAMU	Texas A&M University

CHAPTER I

INTRODUCTION

Optical beam steering can be used for data communication, laser radar, laser sensing, optical camouflage, and weapons [1]. The technology has many significant applications that enable innovation. Many beam steering devices require mechanically moving parts, which provide performance limitations due to vibrations and mechanical wear [3]. It is desirable to use a method of non-mechanical means to increase performance, the lifetime of the device, and response time [2]. We present a phased array, integrated optical beam steering device using thermo-optic heaters. The silicon nitride waveguide array has eight arms that are spaced by 10 μm . Each is connected to a thermo-optical heater that manipulate the phase of the light by changing the refractive index of the medium the light is traveling through. The goal was to demonstrate the ability to steer the beam in different directions by changing the relative phases of the paths with a steering algorithm using thermo-optic heaters. This experiment consisted of optimizing the experimental setup, and simulating the heater-tuning algorithm.

CHAPTER II

METHODS

To correctly steer the far field beam, the zero position voltages for each heater must be found, because the manufacturing variations cause each path to have an initial phase difference. Therefore, the heaters must be tuned so that all arms are in phase and give maximum power. To accomplish this, a proper setup must be built, an electrical control must be design, the heaters must be characterized, and an optimization algorithm must be formulated.

Setup

The measurement setup is a very simple design that allows for maximum stability to get consistent results. This includes a 1550 nm laser source with a connected fiber that is butt coupled to the Si₃N₄ chip. The output of the Si₃N₄ chip is coupled into a collimating lens and a focusing lens, which allows for coupling back into the intensity detector. The detector determines the total intensity coupled in from the targeted lobe.

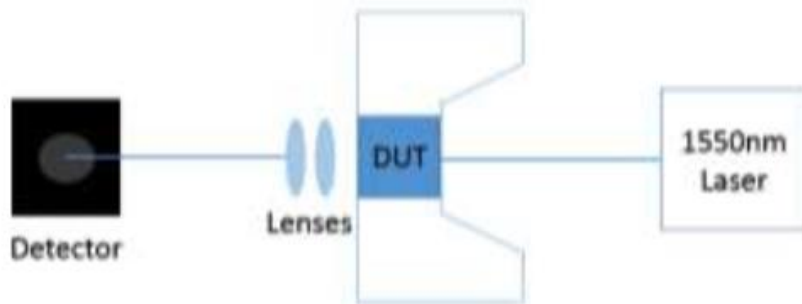


Fig. 1. Measurement setup

We had to ensure stability of the setup because any slight draft or vibrations could cause the detector readings to fluctuate. We tested multiple setups by leaving the device on for a five-minute period and recording the power. Our final stage showed a significant decrease in the fluctuation.

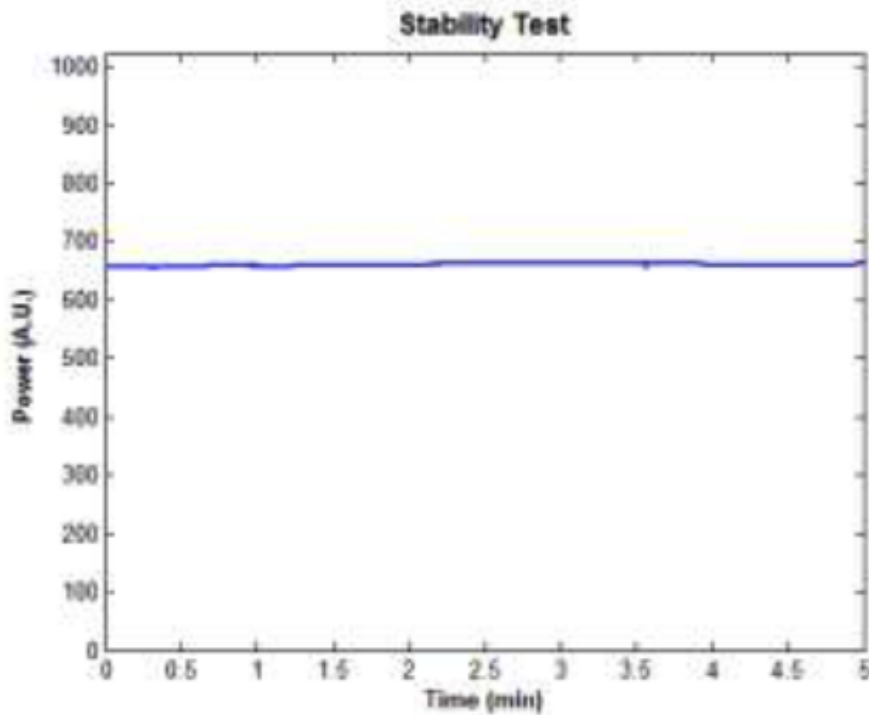


Fig. 2. Stability test results

The fiber, chip, and lens are attached to three stable stages that host micro-adjustments. The butt coupling needed to be very precise in order to get maximum intensity, and the stages allowed us to bring the plane of the chip, source fiber and detector lens into an optimal range. Then to improve the accuracy of the coupling, we added a liquid index to bridge the chip and the fiber. A significant jump in the power occurred but over time the power started to decrease causing our measurements to be imprecise. The phase shifters caused the chip to over heat, which forced the index liquid to evaporate. To get more precise measurements, we design a thermo-electric cooler stage to manage the temperature.

Electrical Control

The fabricated chip was wire bonded to a printed circuit board to allow for easier access of the on chip electrical pads, which permit the desired signal to reach the thermo-optical phase shifters.

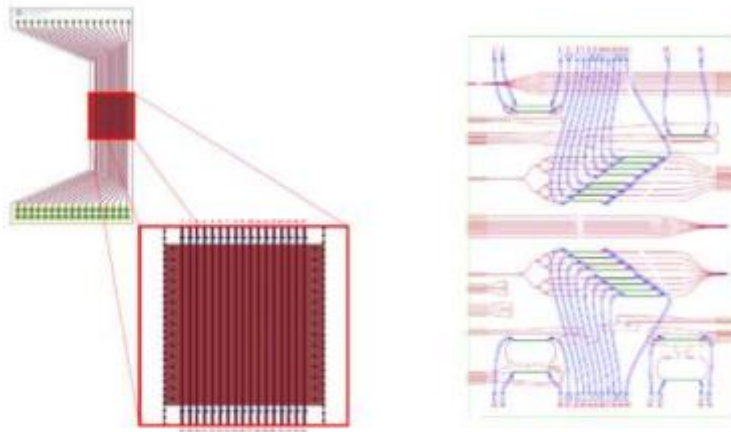


Fig 3. PCB diagram

The heaters needed to be electrically driven simultaneously, so an electrical control with a single high voltage source and a current amplified by digital means needed to be design. An Arduino Mega and a ULN2003A chip was used to electrically control the heaters. The Arduino was connected to potentiometers to provide a manual approach to adjusting the heaters. They were voltage dividers that gave a variable voltage output from 0V to 5V. The output of the potentiometers was read by the Arduino and used to determine the digital output of the pulse width modulation (PWM) that was fed to the ULN2003A chip. The ULN2003A is an array of seven Darlington transistors that amplify current going to the heaters. The following daughter board was created.

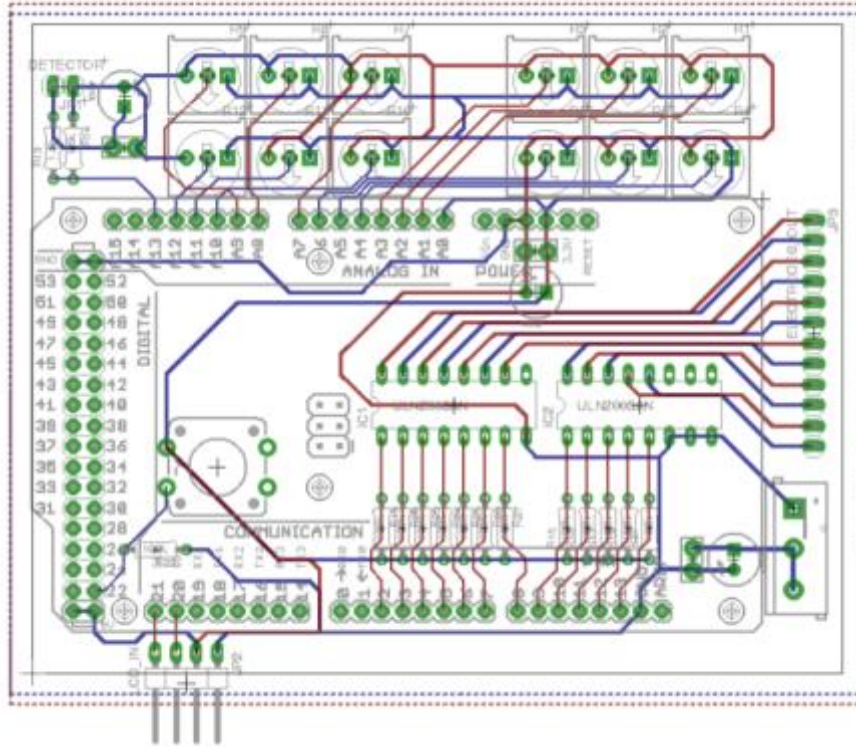


Fig. 4. Daughter board layout

Thermo-optical Heater Characterization

The thermo-optical phase shifters are resistive heaters made from Chromium with Chromium/Gold electrical pads. The resistance of the heaters is 250-300 ohm per 1mm of heater length. The approximate heaters length that we used was 2000 um, and therefore each is expected to have a resistance of 550 ohms +/- 50 ohms.

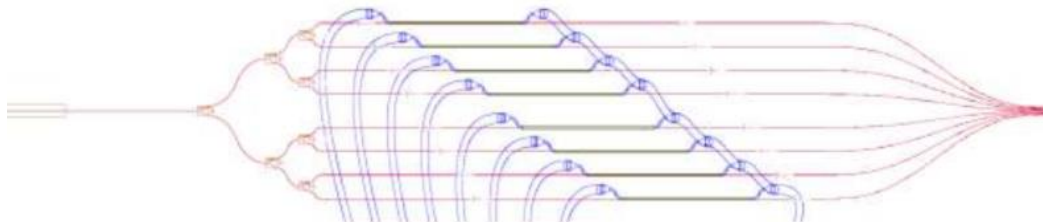


Fig. 5. 1x8 waveguide array

The phase of heaters change linearly with power, so we first need to find the relationship between power and voltage. To characterize the heaters, we fabricated a Mach-Zehnder interferometer (MZI) on the chip, which detects differences in the phase across two paths. We will try to determine the Voltage to Phase relationship by applying voltage to the path with the phase shifter and comparing it to the path without the phase shifter.



Fig. 6. MZI diagram

Using voltage and current measurements taken from the heater, the Power-Voltage relationship was found to be:

$$P(V) = 0.00183V^2 + 0.000511V - 0.001235$$

The Power-Phase relationship was found to be:

$$P(\text{Ph}) = 0.10349\text{Ph} + 0.3632$$

These two equations give a Phase-Voltage relationship:

$$\text{Ph}(V) = 0.017826V^2 + 0.00246V$$

The 2π phase shift voltage is then found to be 18.7V. We then calculate the resolution of our voltage adjustments. The Arduino is capable of increasing the voltage by 256 increments, so we divide 18.7V by 256. This number becomes our ΔV , and with it we determine the largest phase adjustment, ΔPh . We divide 2π into equal parts of length ΔPh and use it to invert the Phase-Voltage relationship. We then approximate the Voltage-Phase relationship and transform it to the

ByteVal-Integer relationship.

$$\text{Ph} = n * 0.048906$$
$$\text{ByteVal} = 13.661(-0.06989\text{Ph}^4 + 0.9772\text{Ph}^3 - 4.784646\text{Ph}^2 + 11.63798\text{Ph})$$

The plot indicates the range and domain of this relationship $n=120$ give $\text{ByteVal} = 247$.

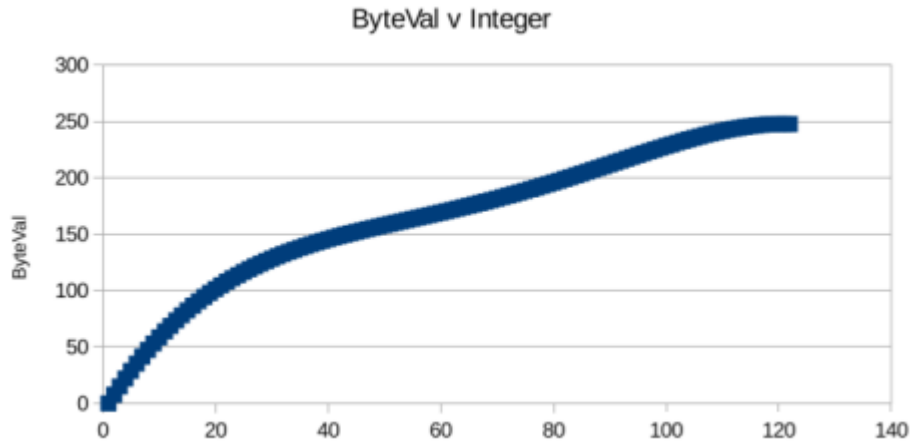


Fig. 7. Byteval Vs. Integer

This information is used to have a better understanding on how to control the heaters from the Arduino using the tuning algorithm.

Optimizing Algorithm

The phases of each channel are random due to manufacturing variations. The purpose of the algorithm is to optimize all the phases to get close to the ideal case with most of the energy in the main lobe. The graph below is the simulated plot of the ideal silicon nitrite optical phased array far field pattern.

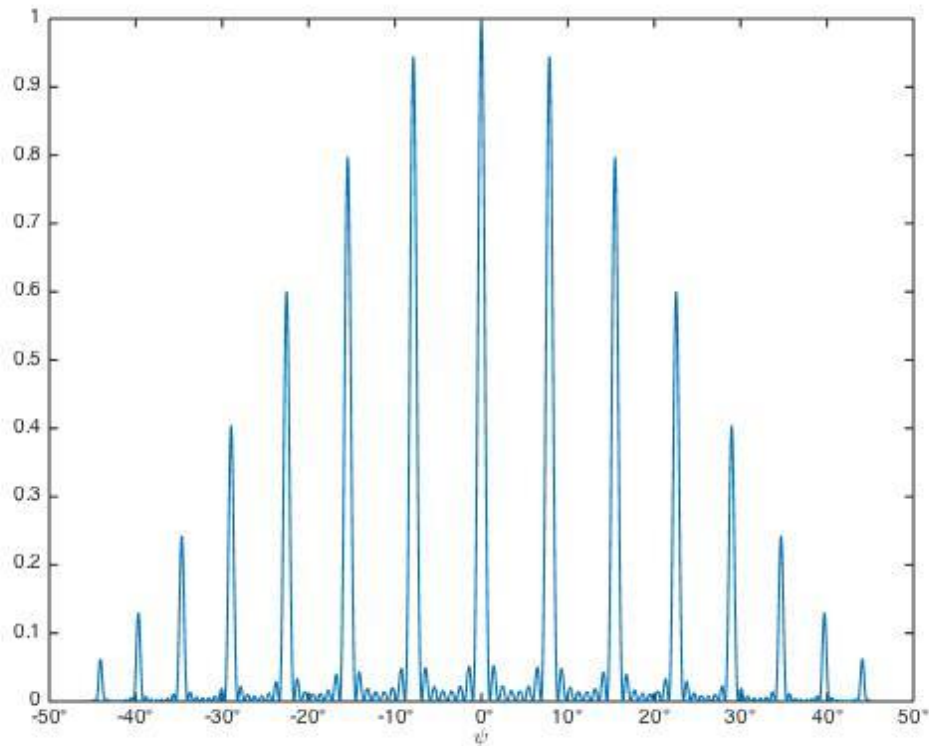


Fig. 8. Far Field Pattern

While taking measurement we would like to capture light from only the main lobe so an acceptance angle of approximately ten degrees is needed. To achieve this, we used a variable aperture that is placed in front of the lens to limit the acceptance of light from the side lobes. In the simulations, different acceptance angles will be tested further to attain the ideal case. To optimize the phases of each path and test our algorithm, we mimic the behavior of the device in MATLAB. We assigned each path a random phase and systematically corrected them by sweeping each channel across a shift of 0 to 2π and selecting the shift that results in the greatest power. The simulation begins scanning at 0 rad and searches for the maximum or the minimum power point. If it finds a minimum, it is then corrected by $+\pi$ to give maximum power. The power is calculated by integrated the function that the destructive and constructive interference of the signals create. The limit of integration is the acceptance angle we choose to test. Ideally

the function of the power will have a Sinc behavior. We simulate the algorithm, and with each iteration it gets closer to the ideal power.

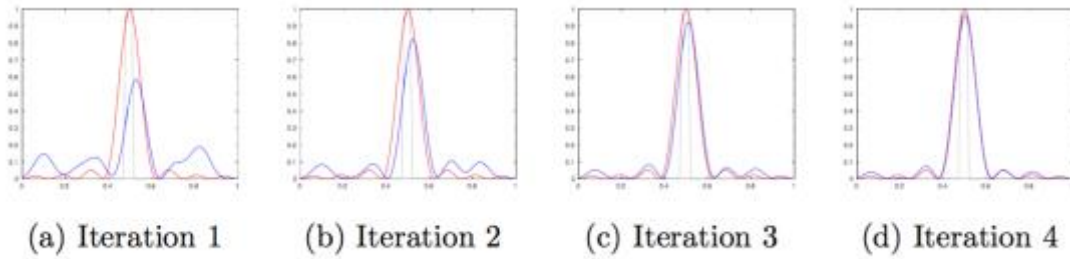


Fig. 9. Correction Simulations

In addition to verifying the tuning technique, we generate an ideal channel response plot.

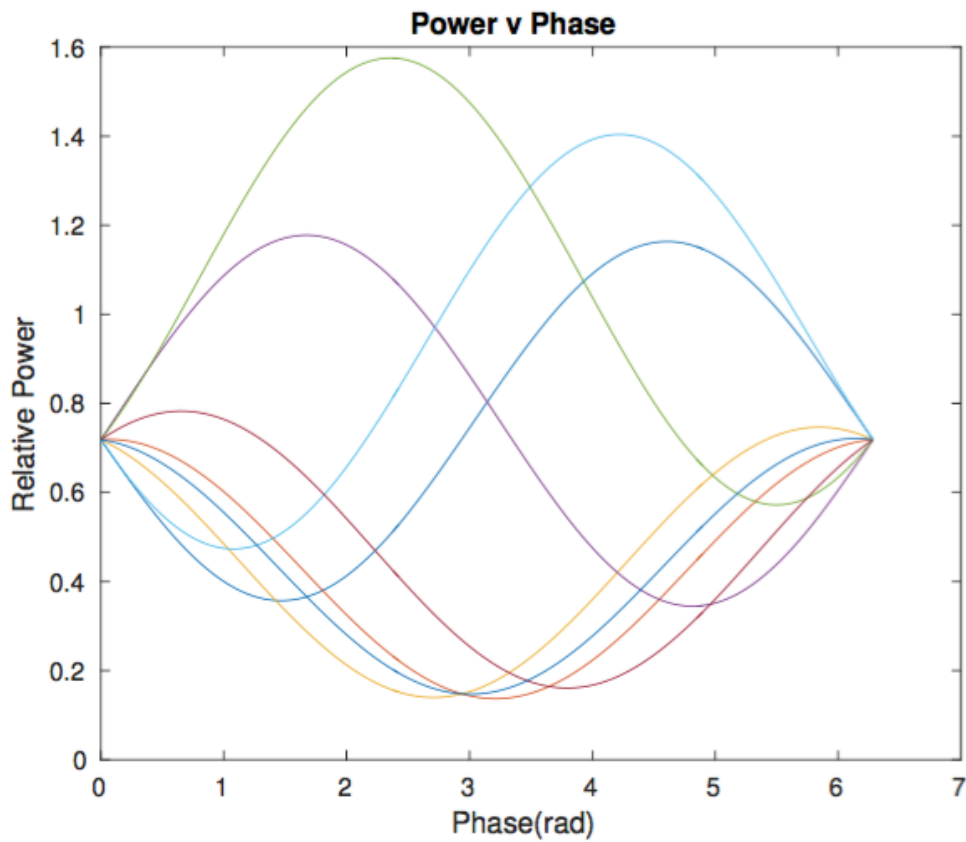


Fig. 10. Ideal Channel Response

IR Camera

To visually see the far field and near field beams of the array we set up an infrared camera that could detect the light. This required the lens to be adjusted as shown below.

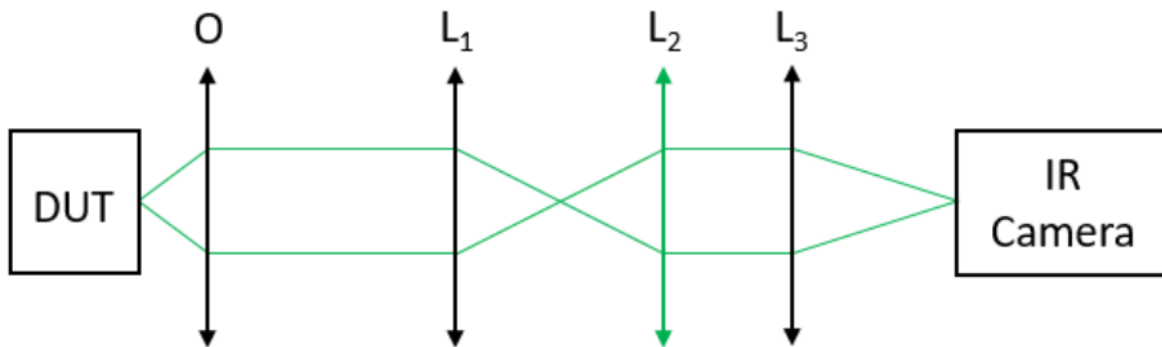


Fig. 11. Near Field Imaging Set up

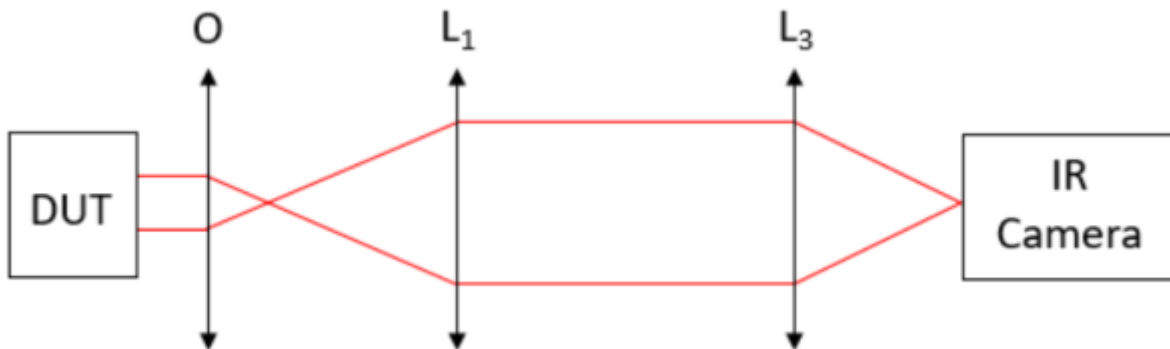


Fig. 12. Far Field Imaging Set up

For our setup, lens L₁ has a Numerical Aperture of 0.39 and focal length of 15 mm, lens L₂ has a focal length of 100 mm, and lens L₃ has a focal length of 50 mm [7]. The NA of the first lens is determined by the angular acceptance of light that is needed from the optical phased array [7].

CHAPTER III

RESULTS

The algorithm was translated and used on the Arduino controller to simulate it on the chip. We tested each channel individually by scanning them through a 2π phase shift looking for maximum intensity output.

Scans before Temperature Stability Stage

The following charts show the relative intensity output as each heater was swept individually from 0 to 2π . All channels are set to a zero-phase shift excluding the one under test.

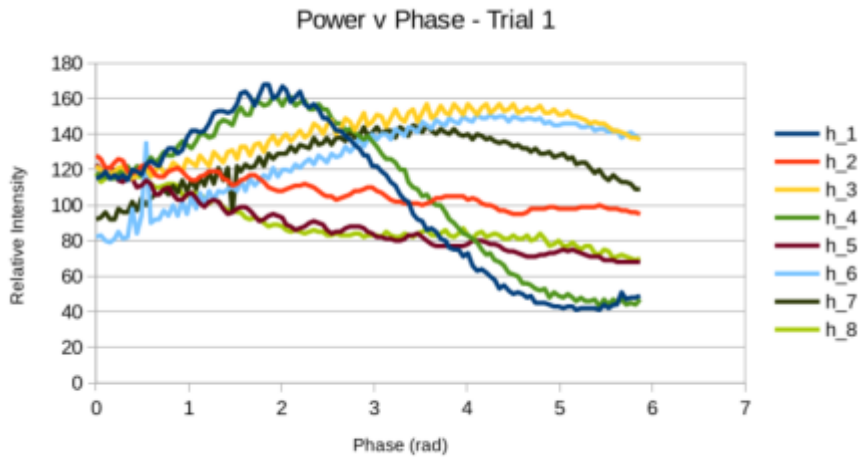


Fig. 13 Forward scan trial 1

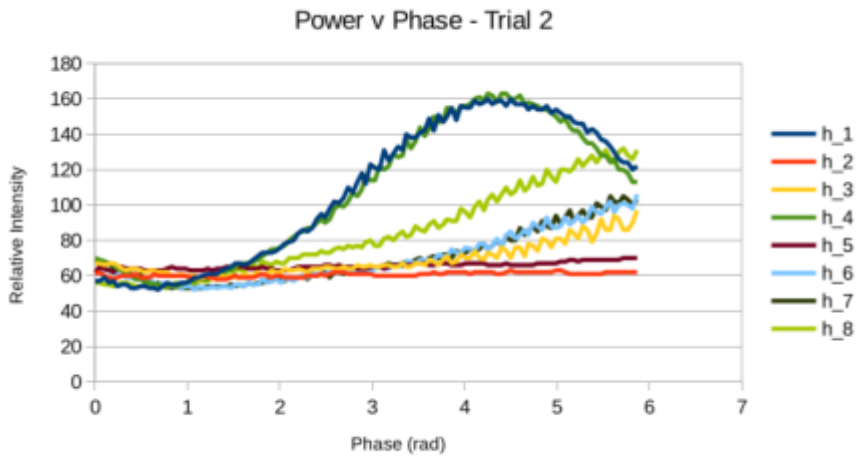


Fig. 14 Forward scan trial 2

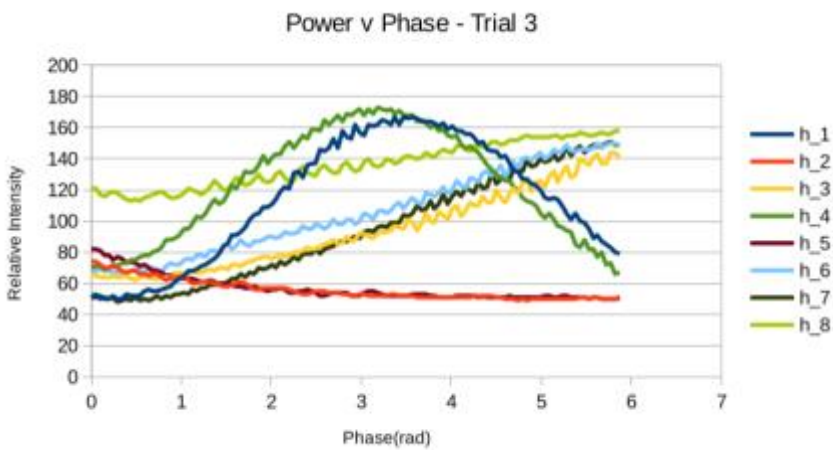


Fig. 15 Forward scan trial 3

There are some degree of consistency for individual heaters, but its concerning that the individual heaters responses do not appear periodic. To determine the if the relative power to phase was consist we ran a backwards scan. The following plots show the power output as each heater was swept individually from 2π to 0.

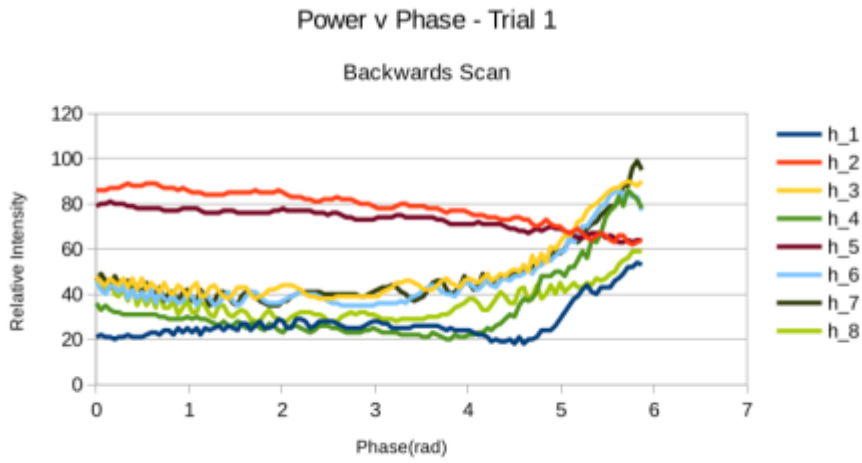


Fig. 16 Backward scan trial 1

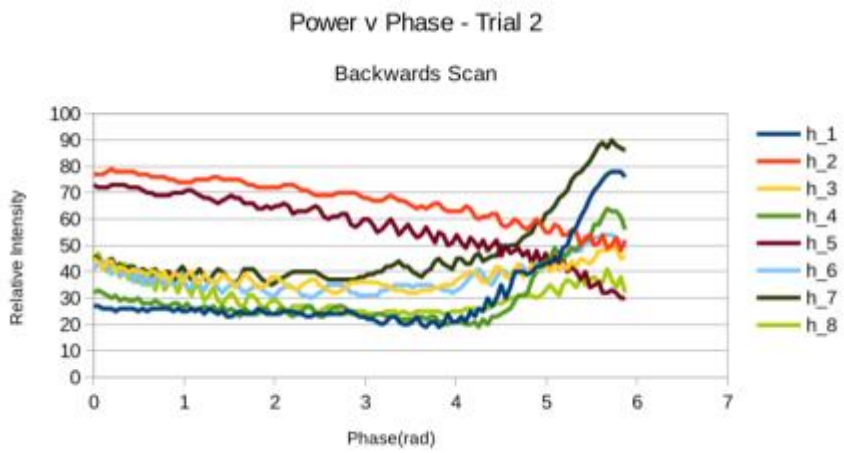


Fig. 17 Backward scan trial 2

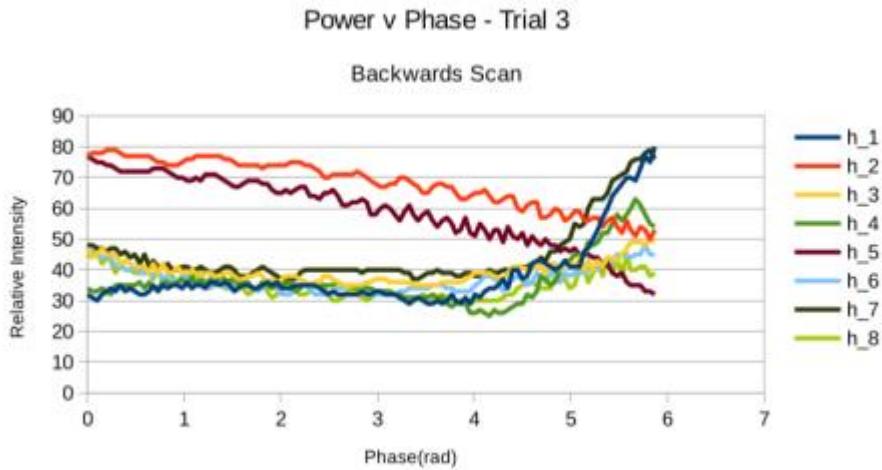


Fig. 18 Backward scan trial 3

The charts show consistency but they are not periodic or do not match very closely with their forward swept counterparts. A significant amount of drift appears in the output, regardless of the heater voltages. It's not uncommon for the power to drift by 10-15% without any changes to the heater. These results demonstrated that characterization of the beam steering chip will have to be done with thermo-cooling stage and a IR camera over the intensity detector. The array projects multiple lobes and there isn't a way to confirm if the intensity detector is calibrated to the main lobe. The variable aperture that is placed in front of the lens to limit the acceptance of light from the side lobes did not prove affective. To get the actual device behavior, the IR camera will have to be used for the analysis.

Scans with IR Camera

The IR camera algorithm operated differently from the previous algorithm. Before the algorithm adjusted the phase based on the total relative intensity, now the algorithm adjusts the

phase based on the total number of pixels received by the IR camera. We created a software that determines the pixels within a targeted area. The graphic user interface is shown below.

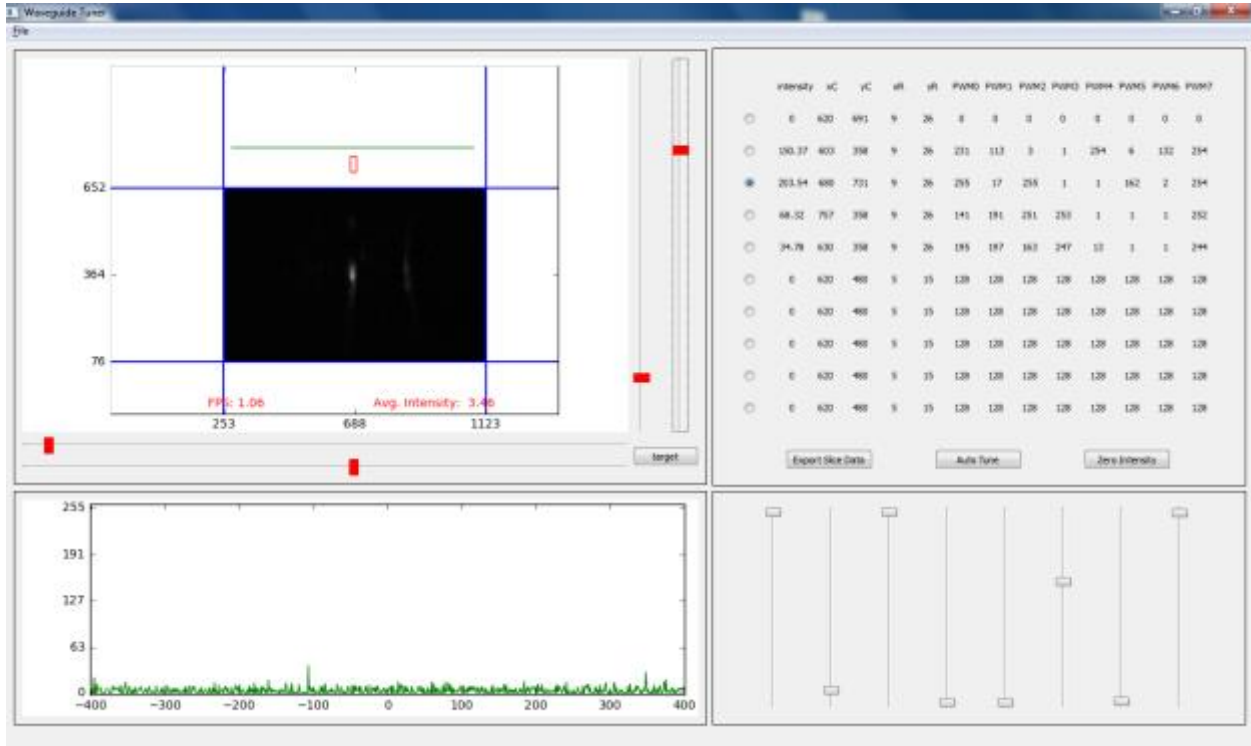


Fig. 19 Graphic user interface of software

The following figure is a flow graph of how the software operates.

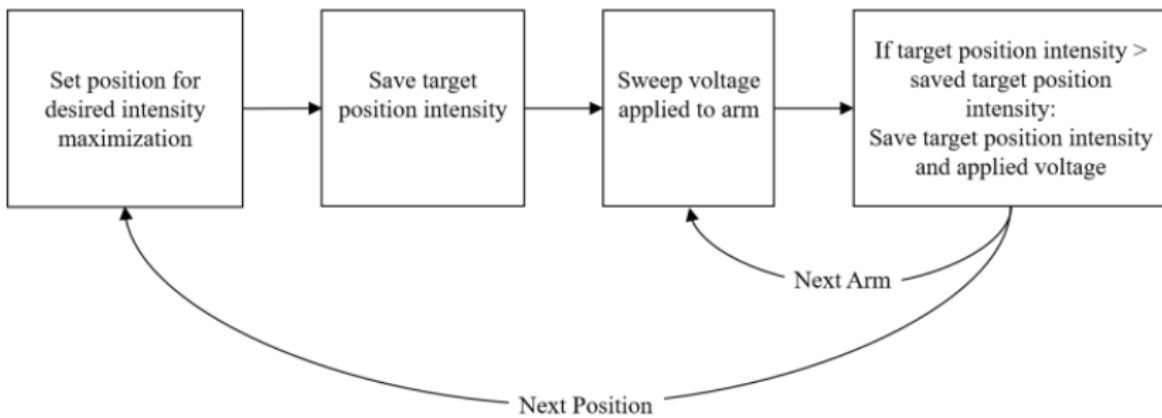


Fig. 20 Flow chart of software tuning algorithm [7]

After integrating the new setup on the chip, the following figures are the images we received from the camera. The first shows the near field, which displays all 8 fibers. Each dot is a ray of light coming out of the fiber. The second image show the far field, which is the result of constructive and destructive interference of the lights traveling in free space.



Fig. 21 Near field Pattern [7]



Fig. 22 Far Field Pattern [7]

We used the algorithm to maximize the pixels in the main beam, then after an allotted period of time we increased the beam significantly. Once the main beam was at its maximum, we targeted a location to the right to steer the beam. The following images are the result of the simulations.

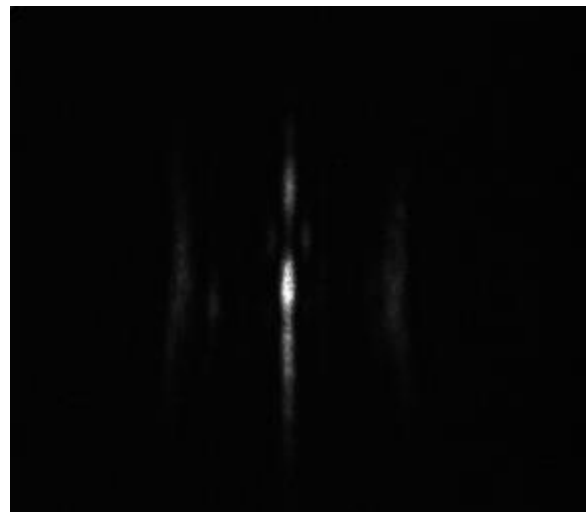
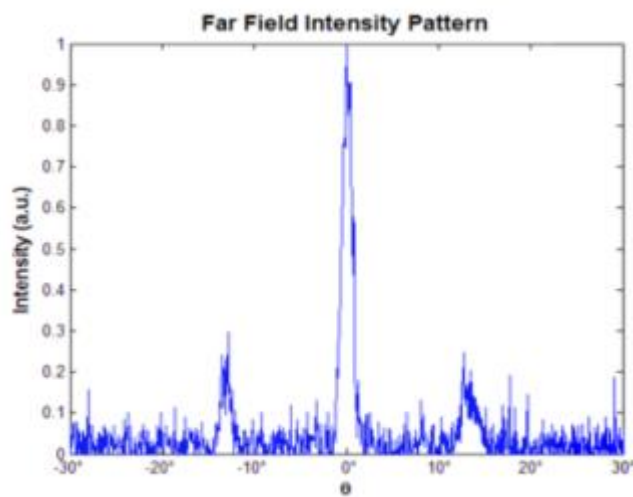


Fig. 23 Main Beam Power Maximized [7]

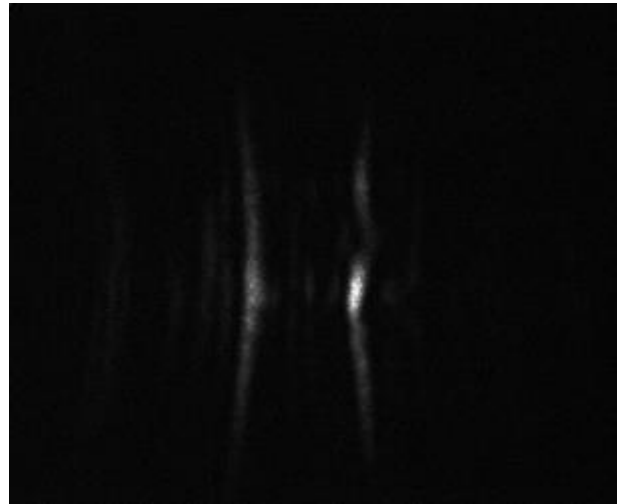
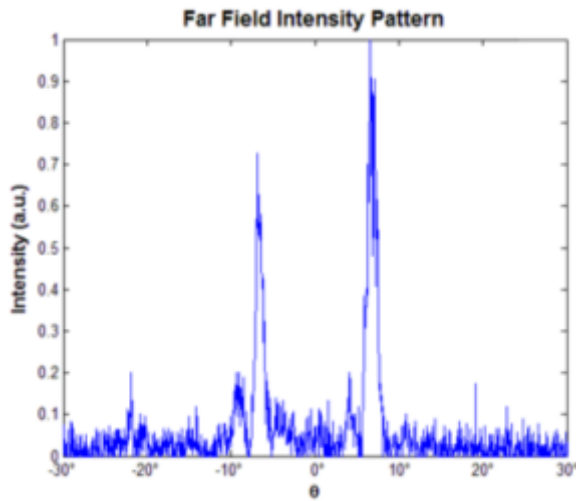


Fig. 24 Main Beam Steered to the right [7]

As we steer the beam to the right we notice another lobe increase in power, and this is due to the array factor and the element factor. If we shift one lobe, the other lobes shift as well and increase the power relative to the element factor. The beam must confine within these limits displayed below.

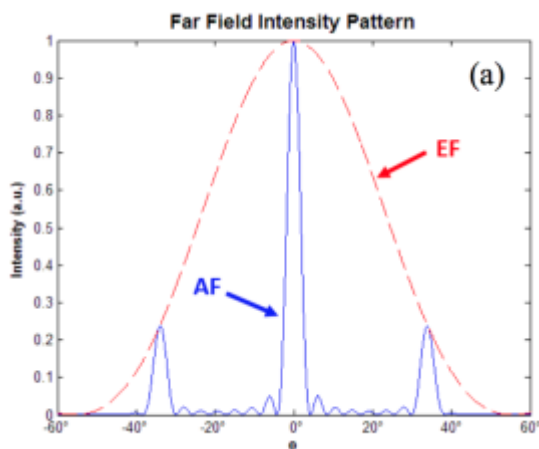


Fig. 25 Main Beam Steered to the right [7]

CHAPTER IV

CONCLUSION

The purpose of this project was to formulate an algorithm that could steer a beam with thermo-optical heaters. We established the algorithm that increased the power and steered the main beam. The phase of each path was corrected to simulate nominal design behavior, but an unwanted drift occurred due to the temperature of the chip. The next step was to integrate the temperature stabilizing system to aid in managing the temperature gradient present on each channel, and this proved effective. Then the use of an IR camera over an intensity detector allowed us to better characterize the steer of the main beam. We have successfully demonstrated the desired device behavior, but further testing is required to quantifying the characteristics of the beam steering chip.

REFERENCES

- [1] Hulme, J. C., Doylend, J. K., Heck, M. J., Peters, J. D., Davenport, M. L., Bovington, J. T., Coldren, L. A., Bowers, J. E. (2014). Fully integrated hybrid silicon free-space beam steering source with 32-channel phased array. *Smart Photonic and Optoelectronic Integrated Circuits XVI*, 1-15. doi:10.1117/12.2044820
- [2] Doylend, J. K., Heck, M. J., Bovington, J. T., Peters, J. D., Coldren, L. A., & Bowers, J. E. (2011, October 18). Two-dimensional free-space beam steering with an optical phased array on silicon-on-insulator. *Opt. Express Optics Express*, 19(22), 21595-21604. doi:10.1364/oe.19.021595
- [3] Jarrahi, M., Pease, R. F., Miller, D. A., & Lee, T. H. (2008). Optical switching based on high-speed phased array optical beam steering. *Appl. Phys. Lett. Applied Physics Letters*, 92(1), 1-3. doi:10.1063/1.2831005
- [4] Davis, S., Rommel, S., Johnson, S., Farca, G., Rebolledo, N., Selwyn, S., & Anderson, M. (2011). Electro-optic steering of a laser beam. *SPIE Newsroom*, 1-3. doi:10.1117/2.1201105.003715
- [5] Aflatouni, F., Abiri, B., Rekhi, A., & Hajimiri, A. (2015, August 04). Nanophotonic projection system. *Opt. Express Optics Express*, 23(16), 21012-21022. doi:10.1364/oe.23.021012
- [6] Ayers, G. J., Ciampa, M. A., & Vranos, N. A. (2010, October 15). Holographic Gratings for Beam Steering. *Field Guide to Lidar*, 1-14. doi:10.1117/3.2186106.ch113
- [7] Macik, D., Bravo, T. E., Pentecost, S. M., Espinal, F. A., (2017). Optimization of Electro-optic phase shifters for integrated optical phased arrays. *SPIE Newsroom*. 1-10. doi: coming soon