Automated Fiber Calibration for Auto Testing of PICs

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***Abstract*— This project centers on enhancing the efficiency and accuracy of fiber alignment in photonic integrated circuits (PICs), a crucial aspect in the testing and development of PIC technology. The traditional method of manual fiber alignment, while widely used, is limited by its time-intensive nature and vulnerability to human error. To address these challenges, our project focused on the development and testing of multiple search algorithms within a simulated setting. The simulation-based approach allowed for a thorough evaluation of these algorithms in a controlled setting, providing insights into their effectiveness and reliability for automated fiber calibration. The main objective was to identify the most efficient algorithm that could potentially replace manual methods, offering a faster, more precise, and error-resistant solution for fiber alignment in PICs. The successful implementation of these algorithms is expected to significantly reduce calibration times, minimize errors, and enhance overall testing procedures in the field of photonic technology. This advancement not only contributes to the technical progress in PICs but also sets a precedent for future innovations in automated calibration systems.**

I. Introduction

In the rapidly advancing field of photonic integrated circuits (PICs), the precision and efficiency of testing procedures play a pivotal role in the development and deployment of these technologies. At the heart of these procedures lies the critical task of fiber alignment - a process that ensures optimal light coupling between an optical fiber and the PIC. Traditionally, this alignment has been executed manually, a method that, while functional, presents significant limitations in terms of time efficiency and susceptibility to human error. Recognizing these challenges, our project embarked on an endeavor to simplify and expediate this process. The primary focus was the development and evaluation of various search algorithms tailored for automated fiber calibration. These algorithms were thoroughly tested within a simulated environment, particularly focusing on optimizing the pitch angle of the fiber on a grating coupler. The simulation-based approach was chosen to provide a comprehensive and controlled testing environment, allowing for an in-depth analysis of each algorithm's effectiveness and reliability. The ultimate goal of this project was to identify a search algorithm that could reliably automate the fiber alignment process without the need for human input. Such a solution has the potential to significantly enhance the efficiency of PIC testing, reducing the time and resources spent on calibration, and minimizing the margin for human error.

II. Recent Advances

In this section of the report, we delve into the latest developments in the field of PICs, particularly focusing on innovations in fiber alignment and grating couplers.

A. *Fiber-array optical interconnection for silicon photonics[1]:*

This paper examines optical interconnects within a fiber array configuration. The paper demonstrates the effect of x, y, and z mismatches to dB loss[1]. This information serves as a crucial reference point, highlighting the stringent tolerances required for optimal fiber alignment[1].

B. *Fully automated in-line optical test system: Advanced materials & photonics[2]:*

This article presents an overview of GlobalFoundries' automated approach to testing silicon photonic wafers[2]. It touches upon optical coupling and automation, providing detailed insights into the tolerances and methodologies presently employed by GlobalFoundries[2]. Notably, several of these methods and tolerances are directly applicable to our automated alignment project[2].

C. *Wafer-level testing of inverse-designed and adjoint inspired dual layer Si-SiN vertical grating couplers[3]:*

This paper explores the application of inverse design methods for developing innovative dual-layer grating couplers. This technique's primary benefit lies in its ability to diminish optical input/output losses in hybrid c-Si/SiN systems[3]. The research substantiates the design's efficacy by demonstrating a marked enhancement in performance[3]. Nevertheless, maintaining a stable and uniform temperature during the crystal pulling process is essential for this method, presenting a significant challenge in its practical implementation[3].

D. *Coupling strategies for silicon photonics integrated chips[5]:*

The article delves into various types of optical couplers used in integrated photonics chips, specifically comparing in-plane and out-of-plane couplers[5]. For the purposes of our project, we are particularly focused on out-of-plane couplers, as these are the types utilized in the ECSyD lab. Out-of-plane couplers offer the notable advantage of providing access to any region of the chip[5]. However, this comes with the trade-offs of reduced coupling efficiency and a more limited bandwidth[5].

E. *Novel Fiber Alignment Method for On-Wafer Testing of Silicon Photonic Devices with PN Junction Embedded Grating Couplers[6]:*

This paper presents an innovative approach to fiber alignment in wafer testing, proposing the integration of PN junctions within grating couplers[6]. This approach suggests that incorporating PN junctions could enhance the performance of grating couplers, making their photocurrent independent of factors like fiber angle, wavelength, and polarization[6]. Although this concept is intriguing and merits future investigation, it falls outside the current scope of our automated fiber calibration project due to the complexity of modeling it in RSoft. However, the approach is interesting and presents a promising avenue for future research.

F. *Fiber-to-chip fusion splicing for low-loss photonic packaging[7]:*

The study introduces an affordable and scalable method for permanently connecting a fiber to a photonic chip with high optical efficiency, utilizing fusion splicing[8]. The key advantage of this technique is its ability to provide permanent optical edge coupling between the fiber and the chip[8]. Additionally, fusion splicing is both a cost-effective and scalable method, making it an ideal choice for mass production[8]. However, this technique is constrained to particular types of fibers and lasers[8]. Regrettably, the method outlined in the study is not applicable to our project, as it requires specific fibers and lasers which do not align with our project's specifications.

III. PROJECT OBJECTIVE

The objective of this project is to develop and implement an advanced automated fiber calibration system for photonic integrated circuits (PICs). This system aims to address the challenges associated with the traditional manual fiber alignment process, which is time-consuming and prone to human error. By implementing multiple search algorithms and optimization techniques, the project seeks to improve the precision, efficiency, and reliability of the fiber alignment process as well as making the whole process automated.

A. *Designing Search Algorithms*

Our goal at the onset of this project was to create three different search algorithms for the user to use in different scenarios. Each of these should have different use cases where they outperform the others to provide sufficient options to the user.

B. *Simulating Grating Couplers*

In order to achieve a significantly robust set of datapoints to test the search algorithms on, the pitch angle sweep range used in this project was from 10 degrees to 170 degrees. While this is an overly large range compared to what most testbench users would consider for pitch angles, it provides a means to better test each algorithm.

It should also be noted that the 2D and 3D geometry used in these simulations is supplied by the RSoft examples and was not generated by our team [8].

C. *Test Search Algorithms*

The testing of the search algorithms should be more than simply testing them on simulated data. An analysis of the algorithms response to noise should be included as well due to the unlikelihood of receiving perfectly clean data from real test bench.

IV. METHODOLOGY

This section outlines the process used to develop these search algorithms within our simulated environment. This was accomplished largely in two steps. Initially, before simulation of the grating coupler was complete, a method was needed to test the search algorithms without simulation data. This was done by creating a function of arbitrary x and y scale that roughly represented what a pitch angle alignment dataset might look like. Once simulation of the grating coupler was completed, the second stage was to test and analyze the performance of the developed search algorithms on the real dataset. A more detailed outline of our development process can be seen below.

1. Literature Review and Analysis:

We begin by conducting a comprehensive review of existing literature in the field. This includes studying current practices in fiber alignment, recent advancements in automation technologies, theoretical underpinnings of photonic systems, and grating coupler devices . The objective of this was to gather insights and identify potential areas for innovation. Additionally, this provided insight as to what the

2. Algorithm Development:

The core of our methodology revolves around the creation of search algorithms. These algorithms are designed to automate the fiber alignment process with high precision. We developed and iterated various algorithms, focusing on alignment of the pitch angle of the fiber. Three algorithms were created for this project.

a. Algorithm 1: Hill Climbing (HC)

This algorithm can be considered as the naïve approach to maxima finding. The algorithm takes in a start point and a resolution size as input parameters from the user when calling it. It then checks points to the left and right of the starting position to see which direction the function increases. Going in whichever direction yields greater coupling than the start points, the algorithm moves in steps of the resolution size until both points next to its current location yield lower coupling i.e. it has reached a maximum. It then returns to the respective pitch angle. It should be noted that this method is unable to move past any local maxima and will only function well on perfectly noiseless data. Additionally, this method can take an extremely long time at smaller resolutions if the starting point is far from the nearest maxima.

b. Algorithm 2: Hill Climbing with Momentum (HCM)

This algorithm functions largely in the same way as the HC algorithm, but with the addition of momentum. Unlike HC, HCM takes in a momentum parameter as well. This parameter dictates the number of steps that the algorithm should take past a peak in the hopes of finding greater coupling. Should a greater coupling value be found, the momentum resets, and the function continues on climbing the function looking for another peak. This algorithm provides a more robust approach to handling noise, but much like the normal HC method, can take a significantly long time to run at smaller resolutions.

c. Algorithm 3: Ben, Ali, n' Gavin (BAnG)

This final algorithm is a method developed by the Silicon Photonic Test Bench Senior Design Team during their fiber alignment process to search a wide area of values in an efficient manner. The algorithm begins by taking in a search range and an end resolution from the user. It checks the values at each end of the range, and then at the center point, storing the highest value. Looking from the perspective of the center point, it determines which of the measured points (the end points in the initial case) yielded a higher result. It then moves halfway from the center point to that endpoint and starts the same process again using only the range between the center point and that end point, effectively dividing the search range in half. The process then repeats, continually finding the greater direction and dividing the range in half until the end resolution is reached, and the pitch angle which measured the greatest coupling is returned.

The idea behind this measure and divide loop is that the larger trends of data will be considered during the initially large steps in the search, while the smaller fluctuations will be considered near the end of the process as the distance between search points decreases. This not only allows for an algorithm that is more robust to noise, but also one that converges faster than the previously mentioned methods. Unlike HC and HCM this method is not dependent on the distance between the starting point and the finishing point of the algorithm. Instead, the number of steps needed to converge on a result is solely dependent on the pitch angle range and the end resolution given as input parameters. This will be discussed more in depth in the results section of this report.

3. Testing the search algorithm :

In order to allow for testing of the search algorithms while the RSoft simulation was being refined and performed, a test function was needed to take the place of simulation results. While the x and y range of this function could be chosen arbitrarily as the algorithms will perform no differently on scaled data, a continuous function that resembled the general trend of the simulated results was chosen. The creation of this function was largely based on our intuition of the pitch alignment process and ended up being rather similar to our final data as can be seen in our results section. The pitch angle data can largely be approximated by a sinusoid and also contains a term to add some noise. To approximate the simulation data the following function was used with a domain of 0 to 6.

$$f(x) = 5\sin(0.9x) + \eta\sin(x)\cos(6x)\cos(16x) + 5$$

Where η is a noise coefficient that can be scaled to increase the prominence of noise in the function. The default noise coefficient used in this report is 0.5.

4. Simulation :

For this project, a 2D simulation of a grating coupler was used to generate the coupling values for each pitch angle from 10 degrees to 170 degrees. Initially, a 3D simulation was used to generate these pitch angles. However, due to difficulties adjusting the launch field in RSOFT and the simulation of each datapoint taking upwards of five hours, the decision was made to switch to a 2D simulation. This dramatically reduced the time to simulate the entire pitch range to roughly 3 hours.

It should also be noted that the 2D simulation used in this project measured the coupling out of a grating coupler to a fiber instead of the reverse. This was done to reduce the complexity of the simulations. However, in theory, the optimal angle for coupling in and out of a grating coupler should be identical.

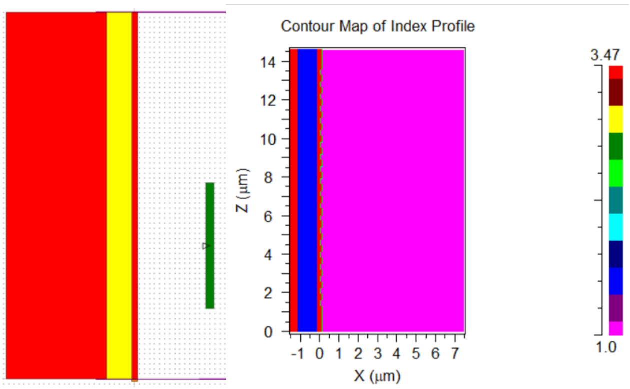

Figure 1: RSoft Simulation Geometry

5. Test Search Algorithms with Simulated Results:

Once the simulation was obtained. We tested the search algorithms we simulated results as well as the results with an introduced gaussian noise to determine the behavior of the BAnG algorithm with respect to noise.

V. RESULTS

This section will discuss the performance of each algorithm as well as discuss potential use cases for each.

1. Hill Climbing (HC)

As the naive method for maxima finding, the hill climbing algorithm performed about as well as can be expected. This method works perfectly with a smooth data function. Each plotted line in Figure 2 represents the starting point and end points of the algorithm when starting at different locations. However, when noise was introduced into the data function like in Figure 3, the simple HC algorithm is easily fooled by local maxima and will not find the global maxima.

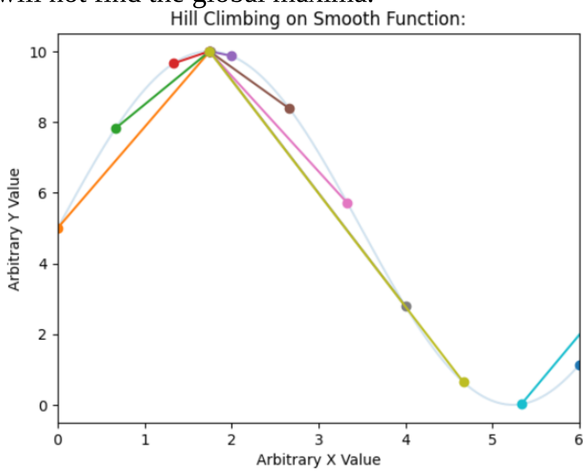

Figure 2: Hill Climbing on Smooth Test Function

This unfortunately makes the hill climbing method not very practical for many real-world applications. However, the general area of the local maxima is already known, which is often the case when performing a fine alignment, the HC algorithm may be a fast, and relatively accurate choice. Of course, this is heavily dependent on how noisy the data received from a test bench is and we unfortunately do not have data on this at this time.

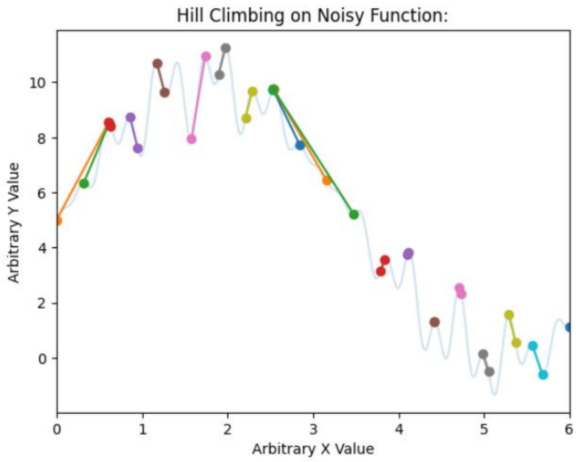

Figure 3: Hill Climbing on Smooth Test Function

Because of the HC methods extreme susceptibility to noise, it performed well on the relatively smooth simulated data, but failed miserably when gaussian noise was applied. In the interest of brevity, these graphs are not included in this report.

2. Hill Climbing with Momentum (HCM)

As mentioned before, the most evident shortcoming of the HC method is its susceptibility to noise. The HCM method is designed to search past local maxima for a certain distance to check for larger values before it returns its best alignment angle. Because of this feature, you can see in Figure 4 that the HCM method improves upon the traditional HC method significantly but requires a much higher momentum such as that shown in Figure 4 to converge on the global maximum.

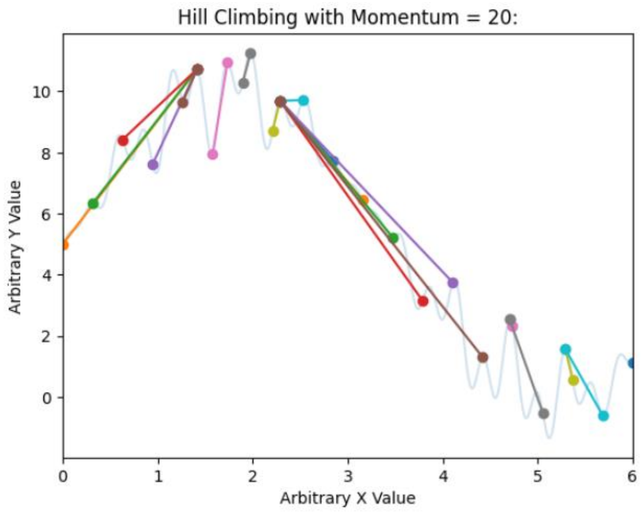

Figure 4: HCM on Test Function with a Momentum of 20.

This behavior shows that larger noise spikes with a relatively low frequency can easily fool the HCM unless unreasonably large momentum values are applied. For example, in Figure 5, where a momentum of 50 is used, the test bench will perform an extra 50 measurements before determining that there are no better values nearby which will take significantly more time than traditional HC. This makes HCM extremely slow, even when compared to HC, and therefore should not be used if the testbench is needed within a short timeframe.

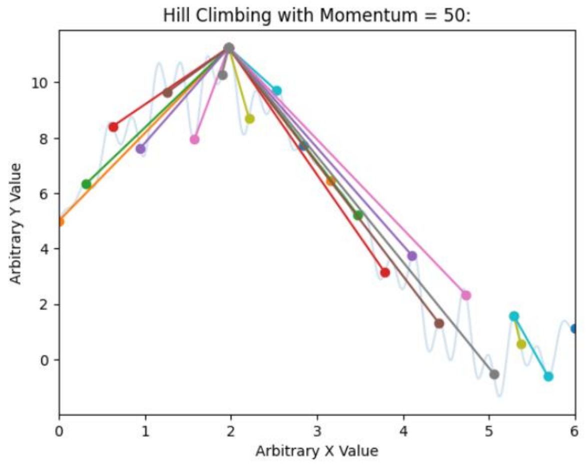

Figure 5: HCM on Test Function With Momentum of 50

Next, the HCM method was tested on simulated data from RSoft. In Figure 5, you can see that despite the starting point of the search, the HCM algorithm successfully converged on the correct pitch angle as expected by a smooth function.

However, when gaussian noise is introduced into the simulated data like in Figure 7, the results of the HCM begin to deteriorate. To test this method's response to noise, the algorithm was called repeatedly with a uniformly random starting point and a different gaussian noise of 0.1 standard deviation each time. The

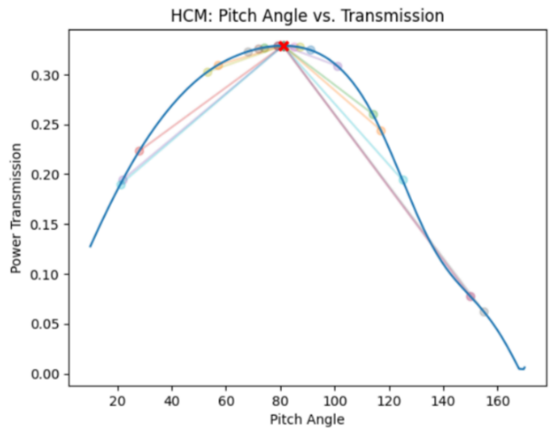

Figure 6: HCM on Smooth Simulated Data 1

Final pitch angles returned are shown as red dots in Figure 7. Note that each different test had a different noise applied to it and that the noisy data shown in Figure 7 is simply for reference, and not the exact data that every test was run on. As can be seen in the figure, HCM is able to converge on the correct area most of the time but suffers a dramatic loss in accuracy. This is most likely due to the algorithm getting stuck on particularly prominent noise spikes. Unfortunately, there is little one can do about this except attempt to minimize the noise in the data.

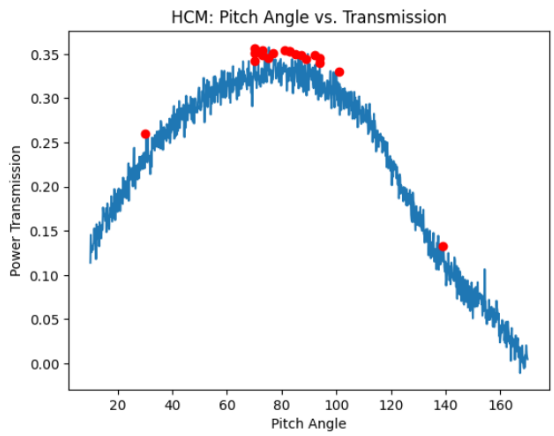

Figure 6: Hill Climbing on Smooth Test Function

All of this considered, HCM may not be a practical method for over a large range of pitch angles. However, if the user knows the general area of the correct pitch angle, HCM may be the best option for performing a fine alignment if time is not a factor.

3. BAnG:

While HCM offers a noise-resistant approach to pitch alignment, a significant drawback persists in both

HC and HCM: time. Linearly searching a function for its maximum can be extremely time consuming with small resolution steps, often requiring hundreds of measurements to be made. For this reason, we propose a search algorithm that begins with larger searching steps and reduces in size as time goes on so that larger trends in the data can be followed before fine tuning towards the end. This method, BAnG, provides a rapid method for searching pitch angles that completely removes the time dependency on the search's start and end points.

For example, Figure 8 shows the search path of the BAnG algorithm on the test function, which is able to find the global maximum within only 8 measurements (each depicted as xs).

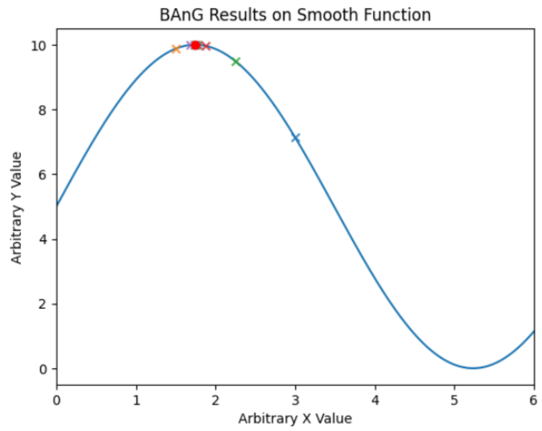

Figure 7: BAnG on Smooth Test Function

Similarly, BAnG performs extremely well on the simulated data shown in Figure 9, taking only 10 measurements to converge on the correct maxima with a resolution of 0.1 degrees. Should a more accurate solution be desired, a total of 13 measurements are needed to reach a resolution of 0.01 degrees with the given search range of 160 degrees.

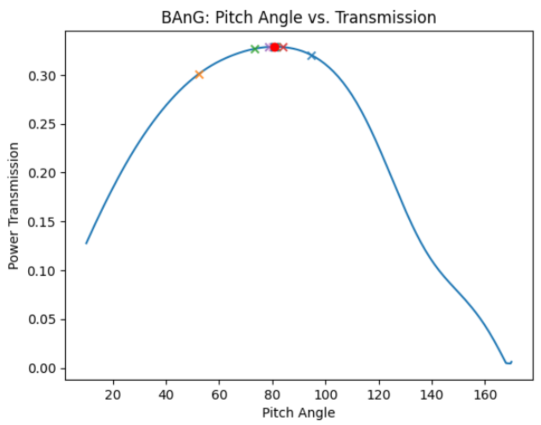

Figure 8: BAnG on Smooth Simulated Data

Additionally, it is not simply smooth functions that this algorithm performs well on. In Figure 10 it can be seen that the BAnG algorithm is able to determine the absolute maxima with no further increase in the number of measurements needed. This makes the BAnG execution time independent of noise which is another improvement over both HC and HCM.

However, testing the BAnG function on a singular noisy function is not sufficient to claim that it is noise resistant. For this reason, it was also tested on the same data function with gaussian noise that was used to test the HCM method. As you can see in Figure 11, the algorithm is easily able to determine the general peak of the of the function while being more resilient to the noise than the HCM method.

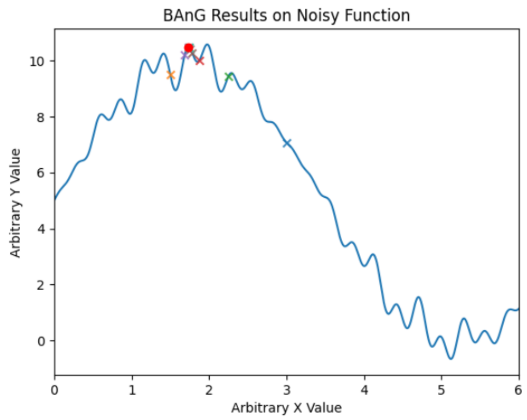

Figure 9: BAnG on Noisy Test Function

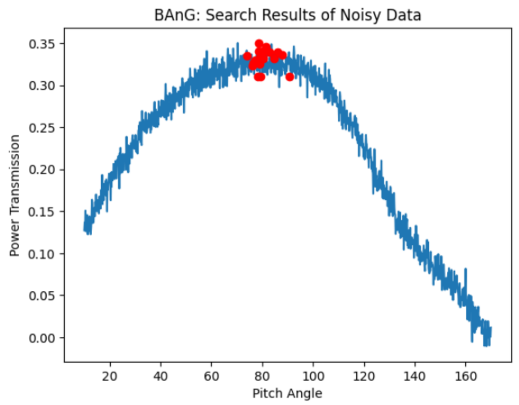

Figure 10: Bang on Noisy Simulated Data

In addition to the relatively less precise grouping of HCM, there are occasions when using HCM where the algorithm gets stuck near its starting point and needs to be run again. Two of these points can be seen as outliers in Figure 7. Note how by using BAnG we have eliminated these outliers. When running this test 300 times to verify, not a single datapoint was more than 20 degrees away from the maximum.

To further examine the effects of noise on BAnG, a plot of the mean average error (MAE) over increasing standard deviations of noise was created. Figure 10 shows the resulting average error of 1000 samples for 100 standard deviations between 0 and 0.1.

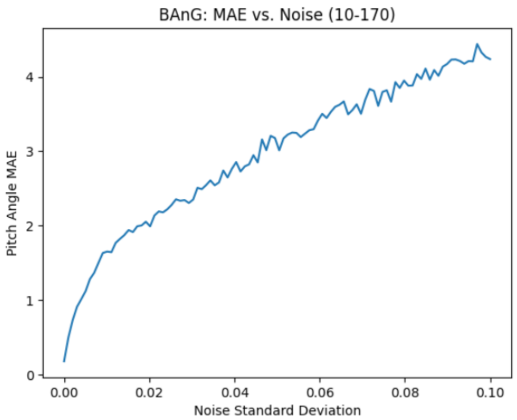

Figure 12: MAE vs Noise

As can be seen in Figure 12, extremely noisy data can lead to rather significant changes in the found pitch angle. Meaning that for larger ranges, BAnG may be extremely effective as a rough alignment technique but can struggle finding fine alignments. However, this can be somewhat compensated for by reducing the search range of the algorithm. For example, by reducing the search range from 160 degrees to just ten degrees as shown in figure 11, the MAE can be reduced to less than half of its original at 0.1 standard deviations.

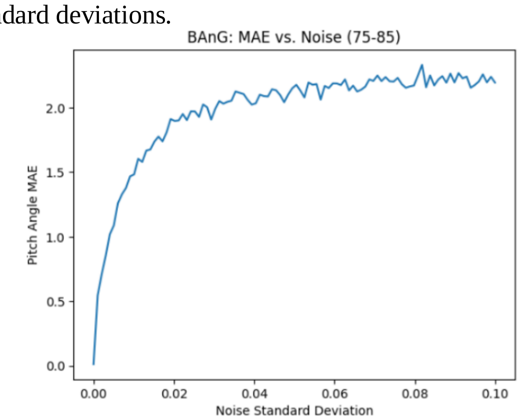

Figure 13: MAE vs Noise (75-85)

Moving on from the analysis of noise, it is important to discuss the speed of the BAnG algorithm. Because this method relies of continually dividing the search range, it converges on a solution quite quickly compared to the other algorithms. The number of measurements required by this method can be characterized by the following equation, rounded down to the nearest integer.

$$n = log_2(\frac{\theta_{max} - \theta_{min}}{resolution})$$

For most applications, this will result in the number of measurements needed to converge on an answer being less than 10. This being said, it should be noted that this method requires significantly more travelling of the fiber angle than the previous two methods. However, this should not be an issue in most scenarios as the time it takes to change the angle of a fiber is usually orders of magnitude times faster than the time necessary to take a measurement.

$$t_{total} = t_{meausre} log_2\left(\frac{\theta_{max} - \theta_{min}}{resolution}\right) + \sum t_{travel}$$

VI. Contributions

For this project, Ali's contributions consisted primarily of working on the grating coupler simulation and exploration. In addition to this, Ali contributed to the research of related works, creation of project presentations, and writing of the introductory, background material, and project objectives for the final report.

Ben's contributions consisted of the creation and testing of the search algorithms. In addition to this, Ben contributed as well to the research of related works and the project presentation. Ben was also responsible for the results, methodology, and conclusion of the report.

VII. Future Work

While this project is primarily a design project for ECE 544, it is important to remember that the problem of fiber alignment on test benches is rooted in a very real scenario. This project's initial goal was to develop and deploy these algorithms on the newly built ECSyD test bench and while the testing of these in theory is great for development, there is still a long way to go before they can be used on a real test bench. For instance, a software package needs to be developed in order to interface these python scripts with the motion controllers and laser. This will hopefully be achieved next semester in Senior Design, and we can tune the algorithms to work more effectively on a functioning system.

In addition to this, a great deal of work can still be done to improve the efficiency and accuracy of these algorithms. One possible way to do this would be to combine the BAnG and HCM algorithm. The BAnG algorithm is extremely good at finding the general area around a global maximum when used on a noisy function. Once this area is localized, it may prove beneficial to perform an HCM sweep with a small momentum value in order to fine tune the alignment.

Finally, while these algorithms are good for finding 1D maxima in pitch angle alignments, using multiple 1D alignments to tune multiple axis (pitch, roll, and yaw) can often miss proper alignment as discussed in [9]. This means that a new algorithm can be made going forward specifically for 3D alignment as a continuation of this project.

VIII. Conclusion

In this project, three methods were created for the automated fiber alignment of PICs. The Hill Climbing (HC) algorithm, although a naïve approach, can be used for quick fine alignment on smooth data, but struggles with noise. The Hill Climbing with Momentum (HCM) algorithm is slightly better at handling noise but comes at the cost of increased time. Finally, the BAnG algorithm was created as an efficient approach to fiber alignment that was resilient to noise, making it good for both general and fine alignment.

These algorithms provide a foundation that the Photonic Senior Design team can use to create an automated fiber alignment process for their soon-to-be assembled photonic test bench. By doing this, countless hours of manual alignment can be saved, allowing the team and all those using the test bench to focus on more pressing matters. In addition, calibrations can be performed significantly more often, leading to consistently strong coupling.

In conclusion, the automated fiber calibration algorithms developed in this project have the potential to significantly reduce calibration times, minimize user errors, and overall streamline the testing procedure for silicon photonic testing.

References

[1] T. Tekin, H. Schroder, L. Zimmermann, P. Dumon and W. Bogaerts, "Fibre-array optical interconnection for silicon photonics," 2008 34th European Conference on Optical Communication, Brussels, Belgium, 2008, pp. 1-2, doi: 10.1109/ECOC.2008.4729467.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] S. Hu et al., "Fully automated in-line optical test system: Advanced materials & photonics," 2018 29th Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC), Saratoga Springs, NY, USA, 2018, pp. 399-402, doi: 10.1109/ASMC.2018.8373215

[3] Thomas Van Vaerenbergh et al 2022 J. Phys. Photonics 4 044001DOI 10.1088/2515-7647/ac943c.

[4] Y. Maeda, T. Miura, S. Matsuo and H. Fukuda, "Accurate Fiber Alignment using Silicon Photodiode on Grating Coupler for WaferLevel Testing," 2019 24th OptoElectronics and Communications Conference (OECC) and 2019 International Conference on Photonics in Switching and Computing (PSC), Fukuoka, Japan, 2019, pp. 1-3, doi: 10.23919/PS.2019.8818134..

[5] Riccardo Marchetti, Cosimo Lacava, Lee Carroll, Kamil Gradkowski, and Paolo Minzioni, "Coupling strategies for silicon photonics integrated chips [Invited]," Photon. Res. 7, 201-239 (2019)

[6] Y. Maeda, T. Miura, H. Fukuda and S. Matsuo, "Novel Fiber Alignment Method for On-Wafer Testing of Silicon Photonic Devices with PN Junction Embedded Grating Couplers," 2018 IEEE 15th International Conference on Group IV Photonics (GFP), Cancun, Mexico, 2018, pp. 1-2, doi: 10.1109/GROUP4.2018.8478727.

[7] Juniyali Nauriyal, Meiting Song, Raymond Yu, and Jaime Cardenas, "Fiber-to-chip fusion splicing for low-loss photonic packaging," Optica 6, 549-552 (2019)

[8] "RSoft." Computer software. Ossining, NY: Synopsys, 2012.

[9] Rong Zhang and F. G. Shi, "A novel algorithm for fiber-optic alignment automation," in IEEE Transactions on Advanced Packaging, vol. 27, no. 1, pp. 173-178, Feb. 2004