Optical Fiber Coupling Progress Report

Arba Shkreli, Elianne Sacher

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Abstract

As part of a class project done for ES158: Optimal Control and Estimation, the following is a progress report on optimal feedback control applied to an optical fiber coupling problem. The setup to be controlled is described along with system modeling and initial control approach. Depending on time availability, the work could evolve into a fully implemented controller on the hardware for which it is needed.

1 Introduction

In a project proposed by Marko Lončar as useful for his lab's work, the aim is to design a controller to align two optical fibers on both ends of a waveguide embedded in a chip in so called "fiber coupling." The problem scale is on the order of microns, and calls for feedback control. The means for feedback is a photodetector measuring the intensity of light that goes through the junction made between the fibers and the waveguide. The mode of actuation is a motorized positioning machine that can be operated manually through computer controls that can move the fiber up, down, left, right, away, and toward the waveguide by varying amounts.

What arises immediately from this setup is that the problem could be formulated as maximizing the intensity of light measured by the photodetector. From what was described and observed, moving the fiber along different directions also brings about more than one local maximum. Therefore, if taking the optimization route the problem will be nonconvex. The discussion on system modeling will provide some physical reasons for this 3, but the primary focus will be how to overcome this and achieve the greatest light transmission.

Occasionally, defects in the chip itself are the culprit for bad light output behavior, and alignment becomes unuseful in those cases. It is not within the scope of this project to identify such an issue, but perhaps as the work progresses a means for detecting setup problems becomes apparent in the performance, or lack thereof, of the controller.

A challenge in the real system is that the current means for actuation have a clear flaw and exhibit hysteretical behavior. When a command is made to move in a given direction, the command may need to be given several times before motion happens. The actuator itself it turns out is open-loop itself, and does not guarantee the motion having taken place. It may be within the scope of the designed controller to handle such a problem, but it is not clear as of yet.

2 Control Question

2.1 Defining the Problem

The primary challenge in the proposed project lies in the precise alignment of optical fibers to a waveguide for efficient light transfer. Given the micrometer-scale adjustments required and the presence of multiple local maxima in the intensity landscape, the control problem is inherently nonconvex. Moreover, the actuation system's hysteresis introduces additional complexity, as it lacks a closed feedback loop to confirm the execution of movement commands. These factors combined necessitate a sophisticated control algorithm capable of navigating a non-linear, multi-peak optimization problem while compensating for the uncertainties in actuation.

2.2 The Goal of the Project

The goal of this project is to develop a reliable and automated controller for the fiber coupling process. The controller must maximize the intensity of light captured by the photodetector, indicating optimal alignment between the optical fibers and the waveguide. It should be capable of handling the intricacies of a nonconvex optimization problem and the inexactitudes introduced by the actuation hardware. Success will be measured by the controller's ability to consistently achieve peak light transmission, thus significantly reducing the time and effort currently required for manual alignment.

2.3 The Application

This controller has wide-reaching implications for fields that rely on precision optical systems, such as telecommunications and advanced physics research. By automating the alignment process, we can expect to enhance the efficiency, reliability, and throughput of optical fiber connections. The advancements from this project could set new standards for optical system performance and pave the way for further innovation in photonics. The detailed understanding and handling of such complex control problems may also find applications in other domains where precision and optimization in the presence of uncertain actuation are critical.

3 System Modeling

3.1 Rationale

Optical fibers function by guiding light through a core via total internal reflection. The spatial distribution of light within the fiber, known as the mode pattern, is a critical characteristic of its optical behavior. In an ideal single-mode fiber, the fundamental mode would carry the light with a Gaussian intensity distribution. However, real-world fibers often support multiple modes, each with its unique intensity pattern. When two fibers with mismatched mode fields are coupled, the overall light intensity pattern at the output does not simply follow a single Gaussian envelope; instead, it becomes a composite of several overlapping modes. These additional modes, while possessing lower intensities than the fundamental mode, contribute to the total transmitted light, creating a more complex intensity landscape. Due to their nonzero amplitudes and phase differences, they interfere constructively and destructively at various points, resulting in a pattern with multiple local peaks within the broader Gaussian envelope.

The primary objective of fiber coupling is to maximize the overlap of the intensity patterns emanating from each fiber. This overlap is critical because it determines the efficiency of power transfer from one fiber to the other. In the context of our project, the goal is to orchestrate the alignment such that the core of the narrow fiber is positioned at the peak intensity of the mode field emerging from the wide fiber. This maximizes the overlap integral, which is directly proportional to the coupling efficiency. The challenge lies in discerning and navigating to the global maximum amid the presence of several local maxima due to the overlapping multimode patterns. The alignment system must, therefore, be sensitive and precise, capable of making fine adjustments to achieve optimal overlap. Our strategy must account for the dimensional disparity between the fibers and the complex intermodal interactions to ensure the alignment yields the highest possible light transmission efficiency.

System Diagram

Figure 1 depicts an optical fiber alignment setup utilized for fiber coupling—a pivotal process in optical communication and signal processing systems. The major components outlined in the illustration include:

- **Input Wire (Optical Fiber):** Representing the transmitting fiber, it carries the optical signal into the waveguide. It is capable of precise positional adjustments in the three spatial dimensions (x, y, and z), enabling meticulous alignment for optimal light coupling into the waveguide.

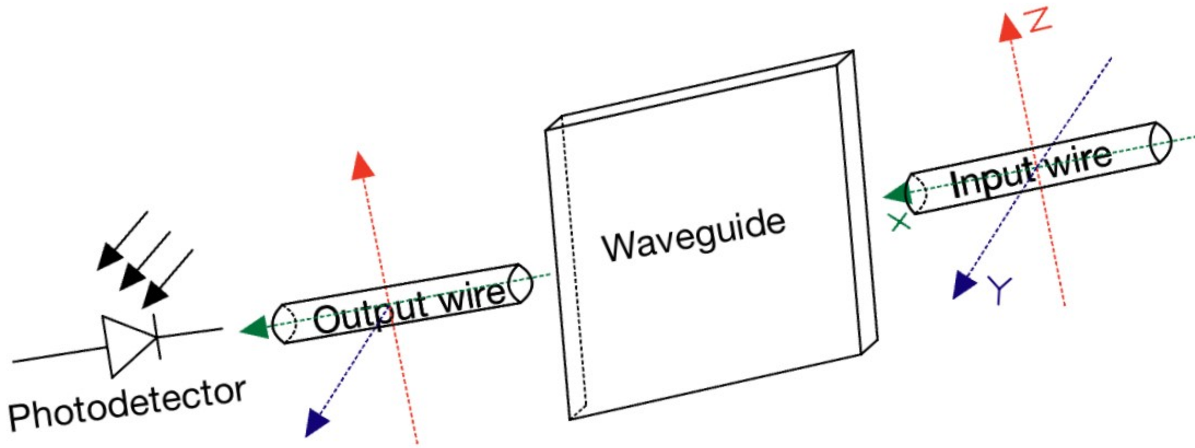


Figure 1: Schematic of the optical fiber alignment setup.

- **Output Wire (Optical Fiber):** This is the receiving fiber positioned on the opposite end of the waveguide. Similar to the input wire, it can be adjusted in the x, y, and z directions. The correct alignment of this fiber is crucial for maximizing the reception of the optical signal exiting the waveguide.
- **Waveguide:** Positioned centrally between the input and output wires, the waveguide serves as the medium for light transmission from one fiber to the other. The alignment of the input and output fibers relative to the waveguide dictates the efficiency of the light coupling process.
- **Photodetector:** Attached at the end of the output wire, the photodetector is instrumental in the alignment process. It measures the intensity of the light that is coupled from the waveguide into the output fiber, providing feedback that is essential for achieving and maintaining optimal alignment.

Each component's ability to move in the x, y, and z directions is critical for the fine-tuning required in the alignment process, ensuring the highest possible efficiency of light transmission through the waveguide.

In our specific setup, there is a considerable disparity in the diameters of the fibers at the coupling point: one end is 3-5 times wider than the other. This discrepancy exacerbates the alignment challenge, as the mode field diameters differ significantly. A narrower fiber, which may be closer to a single-mode operation, will have a more confined Gaussian intensity profile. In contrast, the wider fiber will inherently support a larger number of modes, each with its spatial intensity distribution.

3.2 Assumptions

To streamline the control design for fiber coupling in our optical system, we introduce the following simplifying assumptions:

- **Mode Selection:** The waveguide is capable of supporting multiple modes with varying intensities. For the purpose of this control problem, we focus exclusively on the first mode. This mode has been selected because it possesses the highest intensity, which is directly tied to the effectiveness of our fiber coupling. While higher-order modes may influence the overall light intensity, their effect is considered secondary. Consequently, these modes are deemed negligible for the control model. This assumption allows us to avoid the complexity of multimode interactions and concentrate on maximizing the output of the dominant mode, which is most critical for system performance.

- **Fiber Alignment:** The physical setup includes two optical fibers that need to be aligned with the waveguide. Aligning both fibers simultaneously would indeed yield the most accurate control scenario. However, for the initial phase of this project, we will assume that one fiber has been pre-aligned and optimized. We will then focus our control efforts on the movement and alignment of the single remaining fiber. This reduction in scope from a two-fiber control problem to a single-fiber control problem significantly decreases the complexity of the system, allowing for a more tractable approach to developing and testing our control strategy. Once we have established a robust control solution for one fiber, we intend to extend the methodology to accommodate the second fiber, thereby enhancing the system's fidelity and effectiveness.

These assumptions are made to refine the focus of our project and make initial steps toward our goal both feasible and practical. While they simplify the immediate control problem, they do not overlook the eventual need to address the full complexity of the system in later stages of development.

3.3 Governing System Formulations

This particular optics application requires a beam of monochromatic light to be transmitted at any given time through a circular aperture. The model for the resulting modes for this case is through Laguerre-Gaussian modal decomposition [1]. The first mode, which is the prioritized one, has the following form:

$$I(x, y) = e^{-(x^2+y^2)} \tag{1}$$

Accounting for additional modes (let N be the total number of modes):

$$I(x, y) = \exp\left(-(x^2 + y^2)\right) + \sum_{n=2}^{N} (0.5)^{n-1} \exp\left(-(2)^{n-1}(\sqrt{x^2 + y^2} - 1.5(2)^{n-1})^{2(n-1)}\right) \tag{2}$$

Which outputs an intensity pattern that looks like Figure 2.

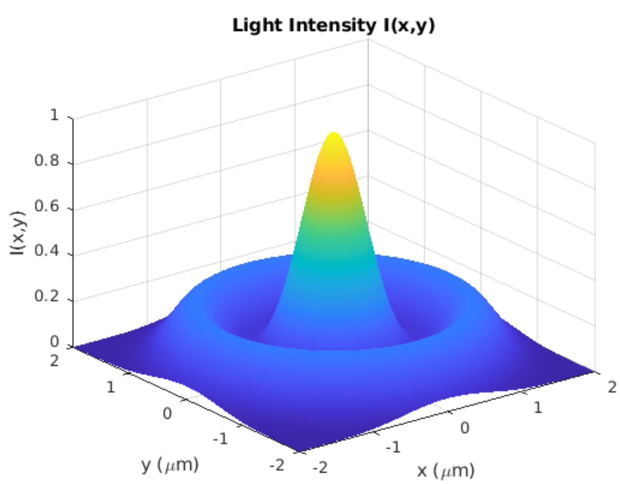
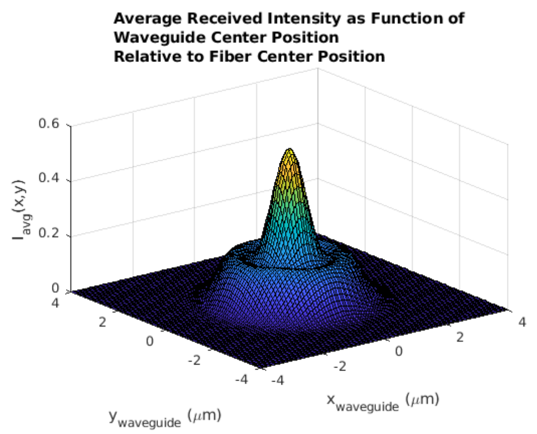


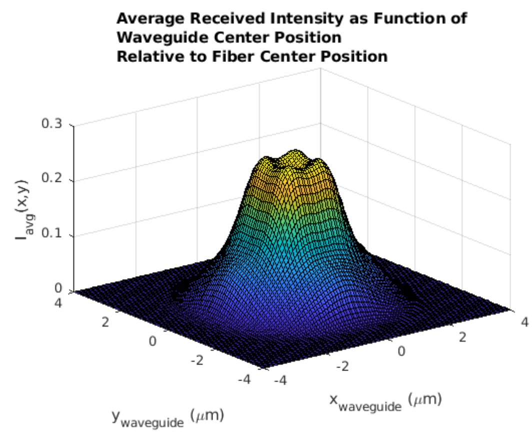
Figure 2: Two-mode light intensity as a function (x,y) from the center of the output of fiber.

An important feature of the expected intensity pattern is the presence of local extrema different from the global optimum. Finding the global optimum therefore is a nonconvex problem. As the project progresses, the aim will be to augment the model to include the light intensity change along the axis parallel to the radial axis of the fibers, z.

As to what the optimal relative position of the waveguide to the fiber should be, there is a dependence on the geometries and sizes of the objects in question. The model chosen is that the fiber is cylindrical (and thus with a circular light output interface) and the waveguide is rectangular. Figure 3 exemplifies how the optimal alignment changes with these factors. The multiple optima in the right case is a result of the assumption that the photodetector perceives the average intensity received through the waveguide. The presence of more than one mode skews where the higher average intensity is since the bigger waveguide "has more choices" in how the second simulated mode is captured.



(a) $1\mu m \times 1\mu m$ waveguide



(b) $2\mu m \times 2\mu m$ waveguide

Figure 3: Different geometries bring about different received average intensity profiles based on alignment

4 Previous Work

Determining ways to perform the alignment coupling requires consulting previous work. While models exist for the light intensity pattern from an aperture, many factors that cannot be modeled for every alignment process such as manufacturing imperfections and nonlinear material properties result in the real light intensity pattern encountered to be actually unknown. Alas, even in the perfect models discussed, the presence of multiple modes makes converging to the

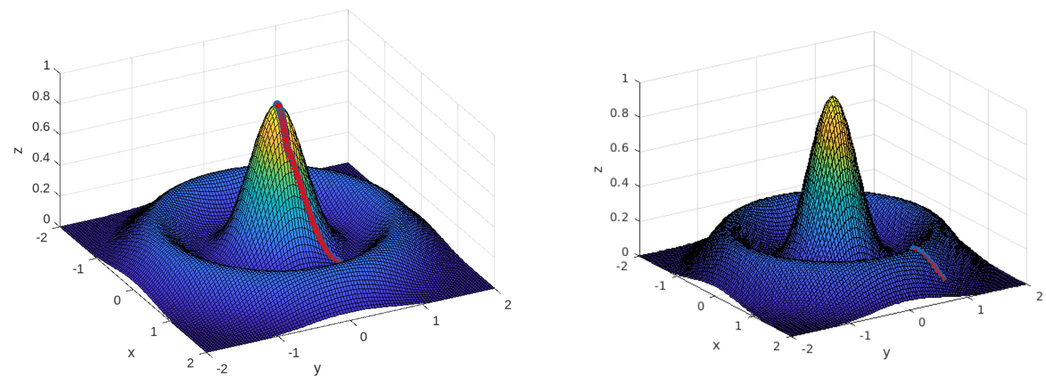
In particular, a setup of fiber coupling and with photodetector measuring the intensity of light passing through to provide control feedback is not new, and has corresponding literature [2]. In the Lončar lab, and as is the case in other contexts, this is done manually in a time-consuming process.

In this realm of application, two main methods for reaching an optimal alignment exist through the Hill-climbing method and the Simplex method (not to be confused with the linear programming solving algorithm).

4.1 Hill-climbing Method

Though the term refers to a large class of algorithms, hill-climbing generally refers to starting with some initial guess for the optimum. At each iteration, all possible moves from the current point are evaluated and the one that results in the greatest improvement is chosen. Variations of this involve more nuanced choices of what the next step of the algorithm should be.

Clearly, the choice of starting point matters for the success of the algorithm being able to reach the global optimum. There are methods that try to address this, but another issue is the number of iterations required to make what is effectively a numerical gradient ascent.



(a) starting at $(x = 0.75, y = 0.5)$

(b) starting at $(x = 1.75, y = 0.75)$

Figure 4: Hill climbing at different starting points. Red points show trajectory. (a) reaches global max while (b) reaches local max.

4.2 Nelder-Mead Simplex Method

For an n-dimensional space, the algorithm starts with (n+1) points at which to evaluate the objective function which form the vertices of a simplex [3][4]. The iterations are a collection of reflection, contraction, and expansion of this simplex until a convergence condition is met. This method is sensitive to the choice of the parameters for the simplex and its evolution in whether it converges to the global optimum. This is a heuristic method that has been employed in a variety of other optimization contexts, but was not for a long time used in photonic applications [1].

5 Picking Initial Approach

5.1 Considerations for Controller

5.2 Problem-Specific Priorities

While a brute-force way to determine the global maximum is to sample as many (x, y) locations and determine the point at which the intensity is highest, there are physical limitations regarding how many times and by how much the fiber can move for the purpose of alignment. Since these are delicate objects, moving them too much can bring the risk of breaking them. The approach should not require much overall motion of the fiber.

The speed of convergence is important, but compared to the manual alignment an automatic approach is generally going to be faster no matter what and certainly requiring less human effort. The previous point of minimizing the overall motion may inherently be linked to the speed of convergence, since it is likely that less overall motion results in faster convergence speed.

The fiber should not make contact with the waveguide throughout the process of alignment. When scoping for points of highest intensity, contrary to the simplified model made, there is z dependence on the intensity of the light, meaning that longitudinal distance from the waveguide can bring about an increase or decrease in intensity. The exact dependece requires more careful modeling. As z alignment is also taken into account, the fiber should never scope too close to the waveguide even if there seems to be an increase in intensity. The challenge in this aspect is that unlike (x, y), where the starting point of the alignment process can be taken to be $(0, 0)$, z can start similarly, but it is hard to know how close to the waveguide the fiber is.

The question of what should be done in the case of two-fiber alignment remains. One-fiber alignment is risky in terms of already potentially requiring a high number of querying points to find the optimum, but increasing the complexity of the output intensity pattern with two fibers increases potential stress on the systems even more. However, as work on the single-fiber alignment progresses, insights for the more complicated case will hopefully surface.

5.3 Current Controller Approach

Since the Nelder-Mead Simplex method was shown to be promising in the domain of photonics applications, the next step is to implement it for the single fiber case first, measure relative performance, and formulate an extension to the two-fiber case. If it is found that too much function probing is needed, a new strategy prioritizing the limiting of motion will need to be investigated. Once the one-fiber case is sufficiently handled, the two-fiber case will make use of the one-fiber solution, and its performance will be measured there also. Since the problem is much more complex than the one-fiber case, there may need to be significant changes made to the approach.

References

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