Measuring the LP Mode Transfer Matrix of Optical Fiber

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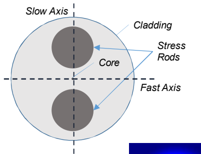
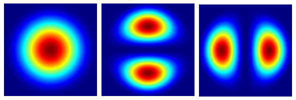
INTRODUCTION

The Transfer Matrix (TM) of an optical fiber characterizes the relationship between the input and output intensity and phase distribution. In this project we seek to measure the TM of Polarization Maintaining Fiber (PMF) in the basis of Linearly Polarized (LP) modes, which form a complete basis for supported inputs and outputs of the fiber.
We investigate two methods for determining the TM. The first method is based on a genetic algorithm. The second method is to directly measure each individual matrix element of the TM. Using a spatial light modulator (SLM) we can control the input mode and characterize the Fourier coefficients of each supported mode at the output of the fiber.



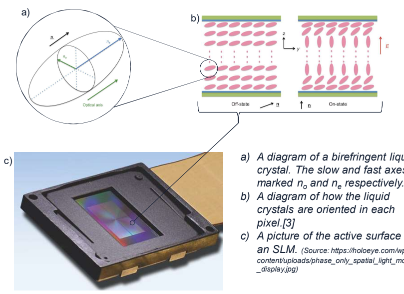
A cross section of a PMF, which is the type of optical fiber used in this project. The stress rods induce birefringence in the fiber core, which reduces polarization crosstalk between the fast and slow axes.



Intensity distributions of the LP modes supported by the fiber used in this project, from left to right: LP01, LP11o, LP11e. Each lobe can be either horizontally or vertically polarized.

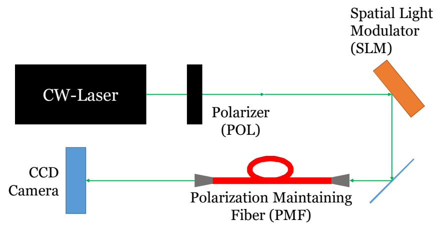
SPATIAL LIGHT MODULATORS[3]

A key piece of equipment in this project is a phase-only SLM. The SLM controls the orientation of birefringent liquid crystals to change the effective path length of light reflecting from the active surface the SLM, which allows the phase of an incident beam to be controlled. The active surface of the SLM is comprised of pixels, and the 'image' comprised of the values set on the pixels is called a phase mask.

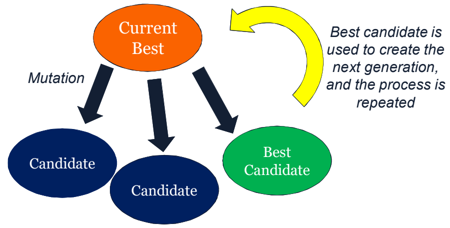


a) *A diagram of a birefringent liquid crystal. The slow and fast axes are marked n_o and n_e respectively.[3]*
b) *A diagram of how the liquid crystals are oriented in each pixel.[3]*
c) *A picture of the active surface of an SLM. (Source: https://holoeye.com/wp-content/uploads/phase_only_spatial_light_modulator_display.jpg)*

METHODS: GENETIC ALGORITHM



The laser is transformed into an LP mode by the SLM, and then coupled into a PMF. The output of the fiber is compared to a target LP mode.
A genetic algorithm is used to alter the input to obtain an output as similar to the target output as possible.



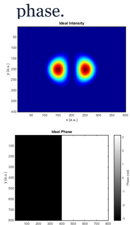
Graphical description of an example genetic algorithm

Superpositions of different LP modes with differing intensity and orientation were used as candidates.
Another way to picture the genetic algorithm is the following:

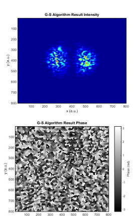
$$\begin{pmatrix} \; \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix}$$

The algorithm searches for coefficients a, b, c such that the output contains mostly a certain target mode and as little other modes as possible.

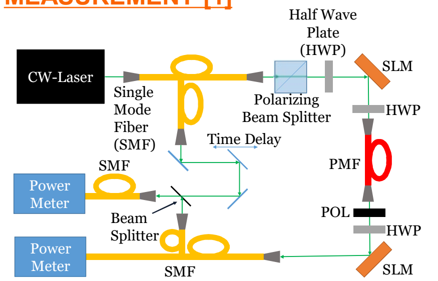
So far measurements with the genetic algorithm rarely converge to a solution. This may be because the Gerchberg-Saxton algorithm, which produced the phase masks, does not reproduce images with the desired phase.



A comparison of the intensity and phase of an ideal LP11 mode (left) and the LP11 result of the Gerchberg-Saxton algorithm (right)



METHODS: MATRIX ELEMENT MEASUREMENT [1]

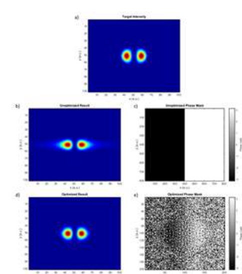


Matrix Element Measurement
After a mode propagates through fiber, it can turn into other modes at the output. This may be represented by an expression such as the following:

$$\begin{pmatrix} c_{01}^{01} \\ c_{11e}^{01} \\ c_{11o}^{01} \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{pmatrix} \begin{pmatrix} \; \\ 0 \\ 0 \end{pmatrix}$$

In this example the coefficients $c_{\alpha\rho\pi}^{\alpha'\rho'\pi'}$ are equal to the first column of the transfer matrix of the fiber and can be measured individually with the help of SLMs. α, ρ, and π denote the angular zeros, radial zeros and parity (even/odd) of the mode respectively. The subscripts apply to the output mode and the superscripts apply to the input mode.

Simulated Annealing
Based on [2], we are attempting to use simulated annealing to create phase masks that will approximate both the correct intensity and phase of desired modes.

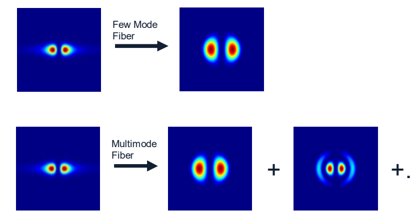


An example result of the simulated annealing algorithm where a) is the target intensity, b) is the result of the initial mask c), and d) is the result of the optimized binary mask e)

Simulated annealing is an optimization algorithm that has a threshold for decreasing the score of a solution to avoid being trapped in local extrema. As the algorithm continues the threshold decreases; the idea is that initially the large threshold will allow the algorithm to find the neighborhood of the global extrema, and at the end the small threshold will make fine adjustments to find the actual global extrema.

CURRENT EFFORTS

Currently we are working on using the matrix element measurement method to characterize a few mode fiber, which does not require the use of simulated annealing. Once we have results for the few mode fiber, we plan to move forward to multimode fibers that will require simulated annealing.



MEEP
To obtain a better picture of how the input Gaussian beam profile is affected by the SLM and subsequent lenses, we are attempting to simulate the laser prior to the fiber using MEEP (MIT Electromagnetic Equation Propagation). We hope that this simulation will give us an accurate picture of how the beam profile is affected after passing through a series of lenses so that we may alter our phase mask generation algorithm accordingly.

REFERENCES

[1] Joel Carpenter, Benjamin J. Eggleton, and Jochen Schröder, "Complete spatiotemporal characterization and optical transfer matrix inversion of a 420 mode fiber," Opt. Lett. **s**, 5580-5583 (2016).
[2]J. Carpenter and T. Wilkinson, "Holographic mode generation for mode division multiplexing," in *Optical Fiber Communication Conference*, OSA Technical Digest (Optical Society of America, 2012), paper JW2A.42.
[3]Z. Zhang, *et al*, "Fundamentals of phase-only liquid crystal on silicon (LCOS) devices," in *Light: Science & Applications* **3**, e213, doi:10.1038/lsa.2014.94

ACKNOWLEDGEMENTS

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