Automated Planar Lightwave Circuits Test Project

Phase I Report:

Establish baseline opto-mechanical motion control and optical power measurement capability.

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Introduction

The goal of this project is to develop, implement, and document Python-based instrument models for the automated testing of Planar Lightwave Circuits (PLCs). This report focuses on phase I of the three project phases. The goal of this phase is to establish opto-mechanical motion control and optical power measurement capabilities using Thorlabs equipment.

Problem Statement

The objective of this project is to create and document Python-based instrument models for automating the testing of PLCs. The Phase I focus will be on characterizing the behavior of a super luminescent diode, utilizing python to control stepper motors and current control to achieve opto-mechanical motion control and optical power measurements.

Equipment List

1. Thorlabs ITC4001: Laser Diode / TEC Controller
2. Thorlabs PM100D: Power and Energy Meter
3. Thorlabs BSC201: One-Channel Benchtop Stepper Motor Controller
4. Thorlabs BSC203: Three-Channel Benchtop Stepper Motor Controller
5. Thorlabs 6 axis NanoMax MAX603D
6. Thorlabs DRV208 Stepper Motors
7. Corning HI1060 Fiber Pigtails
8. Thorlabs SLD
9. Thorlabs DFB

SLD & DFB Characterization

Method

The optical power output from a super luminescent diode (SLD with S/N BOA-54789-45020.4A02) and distributed feedback single-frequency laser (DFB with S/N DFB-63546) were each characterized using current sweeps. The lasers were powered using the Thorlabs ITC4001 laser diode/temperature controller, and the output optical power was measured using the Thorlabs PM100D power meter.

A Python module was developed to control the laser diode controller (ITC4001) through SCPI commands. SCPI facilitated communication of current, temperature, and voltage between the ITC4001 and the computer. The light and current data was stored in an array format, allowing for straightforward plotting using the matplotlib library.

Results

SLD Characterization

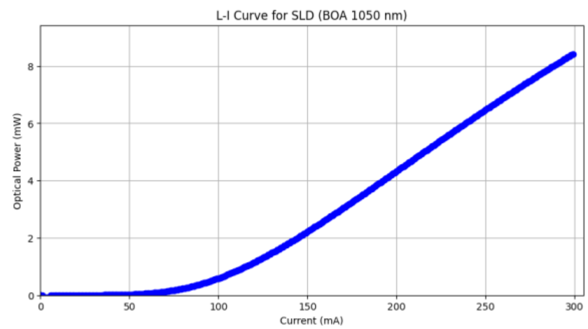

Figure 1. Current sweep for SLD L-I logistic curve (T=25°C)

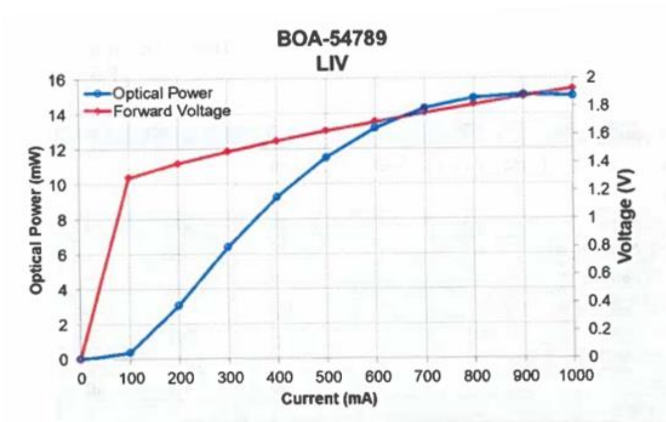

Figure 2. Datasheet LIV chart for SLD (T=25°C)

The optical power output from the super luminescent diode (SLD) was characterized by sweeping the current from 0 mA to 300 mA, with 1 mA step size. For each current value, the corresponding optical power output was recorded, resulting in 300 data points.

The Light Output vs Current (L-I) plot in Figure 1 shows the relationship between the optical power output and the driving current for the 1050 nm SLD. As the current increases, the optical power output also increases, demonstrating the expected nonlinear behavior of the SLD.

Both data sets measure similarly low power output from 0 mA to 100 mA. Above 175 mA, the SLD's output power exceeded the datasheet values. At 300 mA, the SLD produced an optical power output of 8.1 mW, compared to the 6.2 mW specified in the datasheet, as shown in Figure 2. This suggests that the SLD might have better efficiency or less internal loss than expected. More likely, it is due to a difference in calibration between power meters. Additionally, the SLD datasheet shows data up to 1000 mA, but currents above 300 mA were not useful for this experiment, so no data points were collected past 300 mA.

DFB Characterization

The optical power output from the distributed feedback single-frequency laser (DFB) was characterized by sweeping current from 0 mA to 175 mA, controlled via the ITC4001 laser diode controller. Just as done for the SLD, power was measured every 1 mA step.

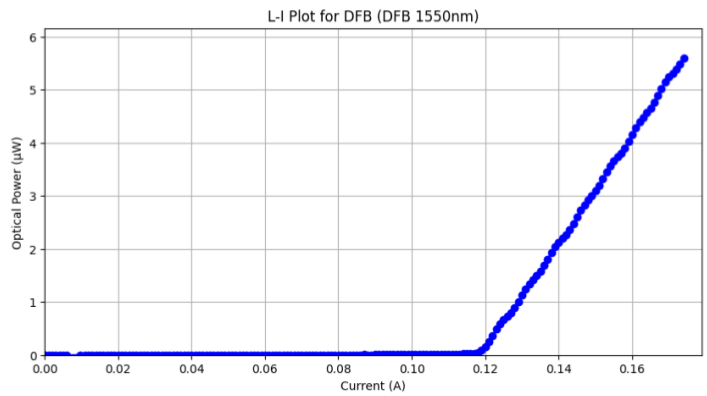

Figure 3. Current sweep for DFB L-I (T=25C)

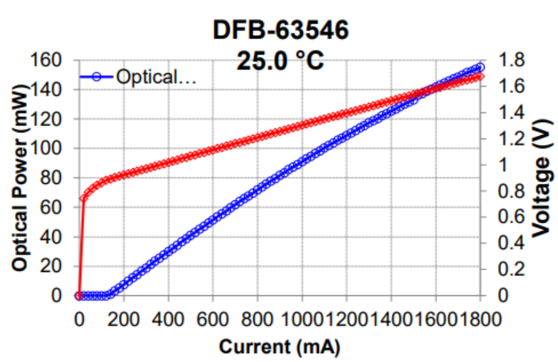

Figure 4. Datasheet LIV chart for DFB

In Figure 3, the current measurements conclude at approximately 175mA, as power output beyond this point exceeded the measurement capabilities of the PM100D power meter. The measured values align well with the expected values, confirming that the DFB butterfly package performs as expected.

Automated Measurement in the Y-Z plane

Method

A Python module was developed to handle both the BSC201 and BSC203 controllers, enabling smooth motion control of the stepper motors for the Y and Z axes. Automated measurements of the 2-dimensional (2D) coupling efficiency map between two HI1060 fibers, were performed by sweeping the Y-axis while keeping the Z-axis fixed, and vice versa.

The tools used included two stepper motors to control the Y and Z axes, a motion controller to manage the stepper motors, a laser diode controller to power the butterfly package, and a power meter to measure the optical output. No specific environmental conditions were controlled during the experiment.

Stepper motors moved in specified directions and distances, allowing the motion control system to align the fibers precisely. YZ profiles were swept at 1-micron steps of the beam in either the Y or Z direction while power was being measured and recorded. The YZ profiles of the sweeps spanned 350 microns, and data was collected for each micron step, resulting in approximately 350 data points per sweep. When sweeping the Z axis, a constant Y position was maintained, and vice versa.

During the experiment, the fibers were held in place with flanges positioned up against each other. Each fiber was recessed approximately 400 microns from the flange face, resulting in a minimum distance of ~800 microns between the two fibers.

Results

The collected data for the optical power output between fibers follows a Gaussian curve. To analyze the collected data, a Gaussian fit was applied using the following function:

```
def gaussian(x, u, sig, max_power):
    return max_power * np.exp(-((x - u) ** 2) / (2 * sig ** 2))
```

This function defines a Gaussian curve where x represents the distance, u is the mean of the Gaussian distribution, sig is the standard deviation, and max_power is the amplitude of the Gaussian curve. The Gaussian fit was applied to the measured data using another function:

```
def fit_gaussian(data):
    distances = data["distance"]
    power_output = data["power_output"]
    max_power = max(power_output)
    initial_guess = [np.mean(distances), np.std(distances)]
    popt, _ = curve_fit(lambda x, u, sig: gaussian(x, u, sig, max_power), distances, power_output, p0=initial_guess)
    u_fit, sig_fit = popt
    x_smooth = np.linspace(min(distances), max(distances), 500)
    y_fit = gaussian(x_smooth, u_fit, sig_fit, max_power)
    return {"distance": x_smooth, "power_output": y_fit}
```

The fit_gaussian function extracts the distance and power output data, calculates the maximum power, and sets initial guesses for the Gaussian parameters based on the mean and standard deviation of the distances. It uses the curve fit function from the scipy.optimize module to fit the Gaussian curve to the data, obtaining the fitted parameters u_fit and sig_fit. The function then generates a smooth range of distance values for plotting the fitted Gaussian curve.

A graph for the Y-axis and Z-axis measurements for both the SLD and DFB are shown below, respectively. The Gaussian fit, applied using the described functions, is shown in red. The Gaussian curve becomes wider as the distance between fibers increases. For the curves shown in Figure 5, the mode field radius(w) obtained from the Gaussian fit are 87.5 µm and 84.5 µm for the Y and Z dimensions, respectively. Similarly for the DFB, in Figure 6, the w obtained as 80 µm and 79.5 µm for Y and Z respectively

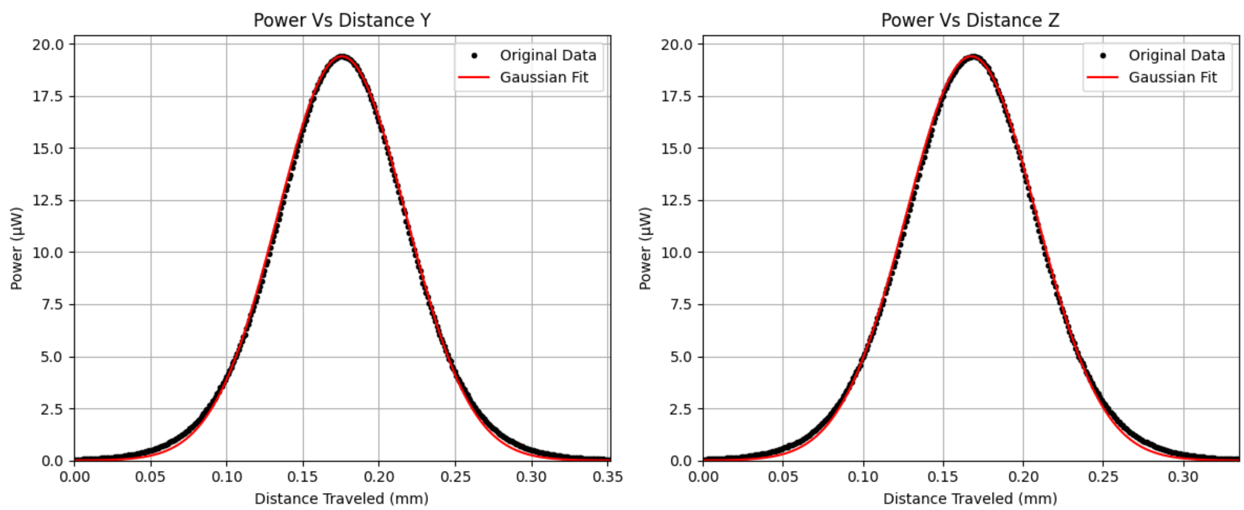

Figure 5. Measured transverse mode profiles for Y and Z planes at closest fiber positions for SLD.

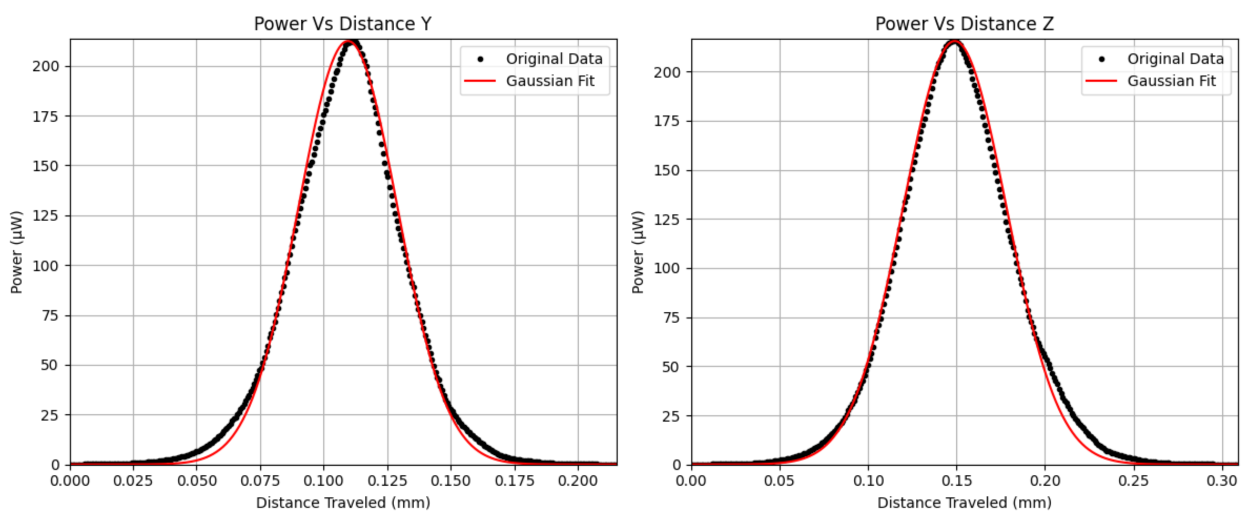

Figure 6. Measured transverse mode profiles for Y and Z planes at closest fiber positions for DFB.

Automated Measurement 3-D Coupling Efficiency

Method

After completing the 2D coupling efficiency measurements, 3D measurement sets were obtained. This process involved sweeping across and measuring the gaussian profiles for both the Y and Z axes, incrementally moving the X-axis backward by 200 micron steps, and repeating the procedure. Throughout the measurements, the position of the stepper motor, the optical power output, and the positions of the two fixed axes were recorded.

Results

Using the recorded data of each YZ "slice," we calculated the laser beam dispersion angle using the mode field diameter of both slices in Y and Z. By utilizing our 1/e threshold points of our Gaussian beam (13.5% of the peak power), we were able to measure the mode field diameter of the beam The Measured mode field radius ($w_{measured}$) of the diverging beam is the mode field of the fiber that is measuring the beam (w_{HI1060})

$$w_{mesured}^2 = w_x^2 + w_{HI1060}^2$$

So, the mode field radius of the diverging beam is given by:

$$w_x = \sqrt{w^2{}_{measured - 3.1um^2}}$$

The theoretical beam dispersion angle for HI-1060 fiber is given by:

$$\theta_{1/e} = tan^{-1}\left(\frac{1050nm}{\pi * 3.1\mu m}\right) = 6.2\ degrees$$

To find the beam dispersion angle, w1 and w2, which are the mode field diameters from different YZ plane profiles, and dx, the distance traveled along the x-axis, were used:

$$\theta = \arctan(\frac{w_1 - w_2}{d_x})$$

The comparison of the calculated values with the theoretical beam dispersion angle validated the measurements.

The calculated mode field radii of the SLD, obtained via a least-squares Gaussian fit, are plotted in Figure 7, The calculated divergence angle from these data is 6.183° and 6.179° in the Y-axis and Z-axis, respectively. This agrees well with the expected value of 6.2 degrees.

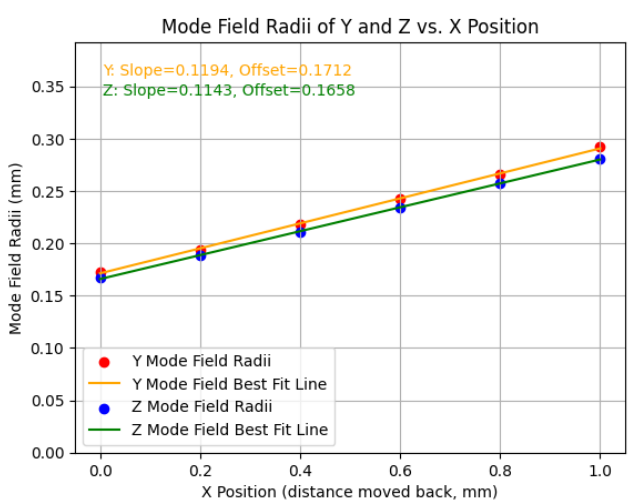

Figure 7. Measured mode field radii as function of axial position for SLD

The calculated mode field radii of the DFB, obtained via a least-squares Gaussian fit, are plotted in Figure 7, The calculated divergence angle from these data is 5.71° and 5.76° in the Y-axis and Z-axis, respectively.

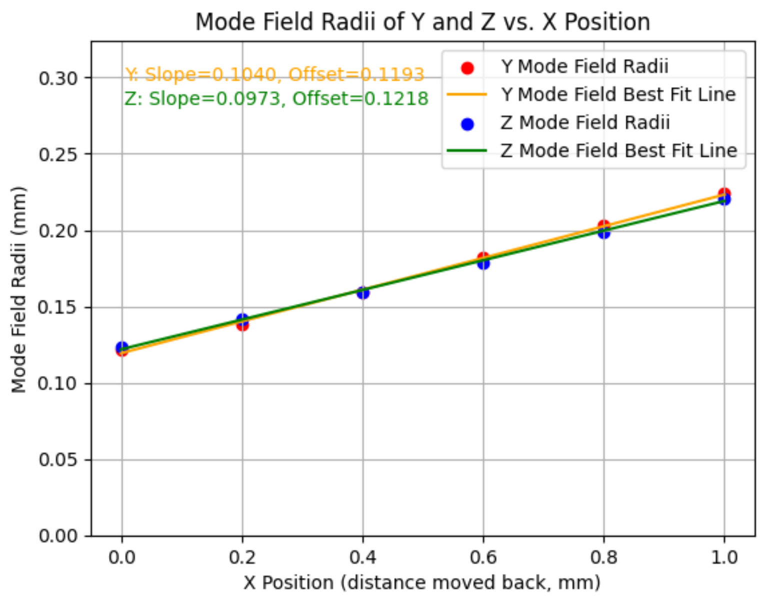

Figure 8. Measured mode field radii as function of axial position for DFB

This agrees well with the theoretical divergence angle of SMF-28, which has a mode field radius, $w_{SMF28} = 5.2\ \mu m$ @ $1550nm$:

$$\theta_{1/e} = tan^{-1}\left(\frac{1550nm}{\pi * 5.2\ \mu m}\right) = 5.4\ degrees$$

The figure below is a heat map of the SLD laser beam, showing the intensity of the beam, where the beam intensity was measured in the YZ plane. This process included sweeping in the Y direction, then resetting Y back to the origin and incrementing the Z axis by a certain distance, followed by sweeping in the Y direction again. After completing this process, the X axis was incrementally moved away from the other fiber by 200 micron steps. The collected data included Y and Z positions stored as a tuple, along with the corresponding power, allowing for effective data plotting. By automating this process, consistent data sets were collected. The power distribution for each slice was plotted as a heatmap, visually representing the coupling efficiency at different axial positions.

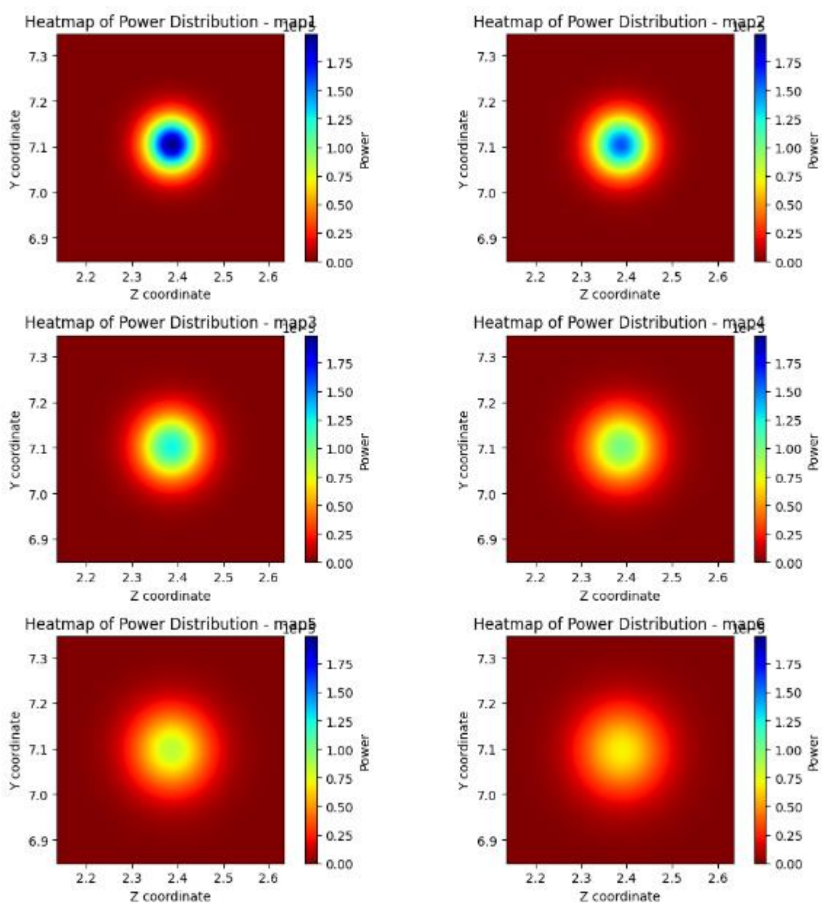

Figure 9. Heatmap representation of the measured power distribution shown of laser beam at different axial positions.

Conclusion

During Phase I of the project, python routines were developed to program and operate the BSC201 and BSC203 motion controllers by interfacing with dynamic linked libraries (DLLs) provided by the manufacturer. Python code was also developed to control the current to an SLD with the ITC4001 Laser Diode TEC controller and measure its optical output power with the PM100D power meter. Combining all this together, an optical power map in the transverse (Y-Z) plane was obtained and showed the expected Gaussian behavior. Excellent Gaussian fits were obtained to the data and enabled accurate determining of the mode field radius from the measured data.

Additionally, multiple Y-Z plane scans were obtained at different axial distances from the fiber, allowing measurement of the beam divergence angle. The measured beam divergence angle agreed well with the expected theoretical value. This resulted in a 3D plot that illustrated the optical power output in three-dimensional space.