STUDY OF MULTIMODE INTEGRATED OPTICAL BENDS

Thesis by
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Abstract

In this research project, the transmission through single and multimode integrated optical bends is optimized with a view towards reducing downstream cost, enhancing efficiency, and providing flexibility. Integrated optics involves the manipulation of light at the micro/nano-scale. It is analogous to integrated electronics. Instead of electronics, light is guided on the surface of an optical chip by integrated optical waveguides. The use of light implies speed and bandwidth. Applications span high-speed telecommunications, sensors, and computing. Optimization of waveguide bends is important since nearly all integrated optical devices employ them. To characterize waveguide bends in the laboratory, optical light is required to be coupled into low cross-section devices. Coupling issues and data collection methods are also studied.
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Chapter 1

1.1 Introduction

Integrated optics is a cutting edge technology. It is the study of optical devices which are based on light transmission in planar waveguides that confine propagating light into regions with very small dimensions, on the order of the optical wavelengths [1]. A dielectric waveguides is a cavity or protrusion that rests on top of a substrate and guides electromagnetic energy (light). The field distributions of the wavefronts created by the electromagnetic energy are called modes. These modes are determined by the angle of inclination; hence, the larger the inclination of the traveling light waves, the higher the number of modes.

Ongoing research deals with the optimization and development of these integrated optical devices. In order to achieve optimization, efforts must be concentrated on specific characteristics of the device. For this research project, that characteristic is the 90 degree bend. The bend is used in most optical devices; thus, its optimization will have a significant impact on integrated optics. For the purposes of this research project, the bend consists of a dielectric waveguide, which redirects electromagnetic energy 90 degrees from its original position. The importance of such optimization is to create a bend structure that offers the advantages of having a high efficiency, a minimal size, and the capability of supporting both single mode and multimode. A high efficiency means the bend will have less loss. A minimal size will not only provide the advantage of cutting costs due to the saving of fabrication space, but it will also allow the device to be used in extremely confined spaces. Being able to support both single mode and multimode adds
to the diversity and freedom of the device. Single mode is usually preferred in long distance transmissions, but multimode is preferred in short distance links. Multimode devices also offer the benefits of simpler interconnection and cheaper costs in packaging due to durability. Research has already been conducted on the optimization of single mode bends [2]. This research project will study and modify the designs created by [2], so that they will be able to support multimode.

1.2 Tasks

There are several tasks that are involved in this research project. First, a theory will be derived and defended for the bending losses of a standard waveguide bend for both modes 0 and 1 using analytical and simulation techniques. Second, the designs from [2] will be studied and a new novel multimode bend structure will be designed using the predetermined bending loss theory. The final bend designs will not be fabricated due to the time constraint of this project. Instead, simulations will be used to provide an accurate representation of their performance. Third, the coupling between a waveguide (device) and an optical fiber will be optimized by tapering the optical fiber. And finally, the data acquisition software will be studied and optimized for accurate and fast data collection. The study of the bend structures and the coupling of the fiber and waveguide will be conducted using R-soft Photonics Suite. R-soft uses Finite Difference Time Domain (FDTD), which is a commercial software and a popular electromagnetic modeling technique. It is easy to understand and implement, and it can cover a wide frequency range with a single run [3].
The third and final tasks of this project deal with the overall test set up. Despite the fact that the main purpose of this research is to study the bend, it is still very important to get a basic understanding of how the test set up works. It begins with a laser source sending a beam of light through an optical fiber and into an optical device. The optical device can have a variety of purposes, such as a power splitter or sensor. The outputted light waves from the device are then coupled into an optical fiber, which is in turn sent to a photodetector. This photodetector is connected to a power meter, which is also connected to a computer via GPIB. The light waves collected from the photodetector are converted to power and displayed on the computer screen using the program LabView. LabView is an industry-leading software tool for designing test and measurement systems. It uses a programming language combined with built-in tools designed specifically for test and measurement making it one of the most flexible and accurate tools on the market [4].

1.3 Mode Bend Research

Before actually getting into the theory of bends, it is important to understand their history and current progress. The history of optics can be dated back many years ago, but it was not until 1969 when it was found that very short optical pulses could be sent through a medium [5]. This discovery sparked a new era and field of study known as integrated optics. Many people quickly picked up the field of study seeing that it had a vast amount of applications and a large future ahead of it. One of the most important features of integrated optics, which is commonly used and widely discussed, is the mode bend. Over many years, much research has been conducted on the mode bend and its
optimization. One of the main goals in the optimization of bends is to reduce its size. While working with the standard curved bends, early researchers conducted experiments to determine the optimal bend radius [6] and loss around sharp turns [7] [8]. When trying to determine the bending losses, several different methods were developed over the years. Some of these methods include: the use of matrices [9] [10], the boundary element method (BEM) [11], and the plane-wave boundary method [12]. With these increasingly advanced techniques in calculating bending loss, the actual bend structures began to change as well. Some of the different types of bend structures throughout time include: standard curved bends, standard curved bends with double or multiple claddings [13], corner-reflector bends [14], abrupt bends using semiconductor superlattices [15], circular hollow waveguide bends [16], 90 degree waveguide bends (similar to the bends in this report) [2], 90 degree waveguide bends using photonic crystals [17] [18], waveguide bends using both conventional index-guided waveguides and photonic crystals together [19], and 90 degree waveguide bends using air trenching [20]. All of these bends were studied and tested mostly supporting only single mode. Later studies started to focus on multimode bends. Some of these studies included: standard curved bend waveguides [21], bent rib waveguides [22], and most recently in 2007, 90 degree standard bend waveguides [23]. So far, no studies have been conducted on the designs in this report using multimode.
Chapter 2

2.1 Theory of Bending Loss for TE Polarization

Dielectric waveguides cannot guide electromagnetic energy around bends without losing power by radiation. Figure 1 shows how these wavefronts move around a standard bend [24]. It can be seen in this figure that the outside wavefronts have to travel a further distance than the inside wavefronts. This means that in order to have a low loss output, the outside wavefronts would have to travel faster than the speed of light to catch up with the inner wavefronts.

![Wavefronts around a curved bend](image)

The most basic equations for a straight waveguide must be used as the basis for calculating the bending loss. These equations and their parameters are [25]

\[ E_y(x) = A \cos(\kappa x) e^{-\sigma(x-a)} \quad x > a \]  
\[ E_y(x, z) = A \cos(\kappa x) e^{-\sigma(x-a)} e^{-j\beta z} \quad x > a \]  
\[ \sigma = \sqrt{\beta^2 - k^2 n_o^2} \quad \kappa = \sqrt{k^2 n_1^2 - \beta^2} \]
The following equations are evaluated assuming transverse electric (TE) polarization. By looking at Figure 2, this means that the polarization of field is in the y direction.

![Figure 2: Parameters for waveguide bend [24.]]

By using the straight waveguide equations and parameters, a set of similar equations can be evaluated for a waveguide bend (see Figure 2) [24]. These equations are as follows [25]:

\begin{align}
E_y(r) &= BH_v^{(2)}(n_o kr) \quad r > r_o \\
E_y(r,\phi) &= BH_v^{(2)}(n_o kr) e^{-i\nu\phi} \quad r > r_o
\end{align}

Using the figure, it can be seen that the only unknowns in the above equations are B, \(\nu\), and \(H_v^{(2)}(n_o kr)\). Assuming the propagation constant in a bent waveguide is nearly the propagation constant in a straight waveguide, the following approximations can be made for \(\nu\):

\[ \nu \approx \beta R \quad \Rightarrow \quad e^{-i\nu z} \approx e^{-i|\beta|z} = e^{-i\beta z} \]
When solving for \( B \), the first step is to begin with [24]:

\[
\frac{v}{n, kr} = \frac{\beta R}{n, k (R + x)} = \frac{\beta}{n, k (1 + x/R)} \approx \frac{\beta}{n, k} (1 - x/R) > 1
\]  

(7)

When \( \frac{v}{n, kr} > 1 \) \( \Rightarrow \) \( H_v^{(2)}(n, kr) \approx \frac{j e^{v(\alpha - \tanh(\alpha))}}{\sqrt{(\pi/2)v \tanh(\alpha)}} \)  

(8)

Where \( \alpha = \cosh^{-1}\left(\frac{v}{n, kr}\right) \) \( \Rightarrow \) \( \cosh(\alpha) = \frac{v}{n, kr} \)  

(9)

Now by approximation [24]:

\[
\tanh(\alpha) = \frac{\sqrt{\cosh^2(\alpha) - 1}}{\cosh(\alpha)} = \frac{\sqrt{\frac{v^2}{n_o^2 k^2 r^2} - 1}}{\frac{v}{n_o kr}} = \frac{\sqrt{v^2 - n_o^2 k^2 r^2}}{v}
\]  

(10)

And by also using \( r \approx R \) [25]:

\[
v \tanh(\alpha) = \sqrt{v^2 - n_o^2 k^2 r^2} \approx \sqrt{v^2 - n_o^2 k^2 R^2} = R \sqrt{\beta^2 - n_o^2 k^2} = R \sigma
\]  

(11)

Now by using the above equation, \( \alpha \)-tanh(\( \alpha \)) from the \( H_v^{(2)}(n, kr) \) equation can be approximated [25]:

Define \( u = \tanh(\alpha) \) \( \Rightarrow \) \( \alpha = \tanh^{-1}(u) \)  

(12)

\[
u^p = (\tanh(\alpha))^p = \left( \frac{\sqrt{\beta^2 R^2 - n_o^2 k^2 r^2}}{\beta R} \right)^p
\]  

(13)
Now by plugging in $r = R+x$, reducing, and neglecting small terms:

$$u^p \approx \left( \frac{\sigma}{\beta} \right)^p \left( 1 - \frac{P}{2} \left( \frac{n_o^2 k^2 2 x}{\sigma^2 R} \right) \right)$$

(14)

So,

$$\alpha - \tanh(\alpha) = \frac{1}{3} \left[ \frac{\sigma}{\beta} \right]^3 - \frac{1}{3} \left( \frac{n_o^2 k^2 x}{\sigma^2 R} \right) + \frac{1}{5} \left[ \frac{\sigma}{\beta} \right]^5 - \left( \frac{n_o^2 k^2 x}{\sigma^2 R} \right)^2 + \cdots$$

$$\alpha - \tanh(\alpha) = \frac{1}{3} \left[ \frac{\sigma}{\beta} \right]^3 + \frac{1}{5} \left[ \frac{\sigma}{\beta} \right]^5 + \cdots - \left[ \frac{\sigma}{\beta} \right] \left( \frac{n_o^2 k^2}{\sigma^2} \right) \left( 1 + \left[ \frac{\sigma}{\beta} \right]^2 + \left[ \frac{\sigma}{\beta} \right]^4 + \cdots \right)$$

$$\alpha - \tanh(\alpha) = \tanh^{-1} \left( \frac{\sigma}{\beta} \right) - \left( \frac{\sigma}{\beta} \right) - \frac{\alpha}{\beta R}$$

(15)

Now,

$$v(\alpha - \tanh(\alpha)) = \beta R (\alpha - \tanh(\alpha)) = \beta R \tanh^{-1} \left( \frac{\sigma}{\beta} \right) - \sigma R - \alpha \sigma$$

(16)

Now by plugging this into the $H_v^{(2)}(n_o kr)$ equation [24]:

$$H_v^{(2)}(n_o kr) = \frac{i}{\sqrt{\pi/2} \sigma R} e^{\frac{\beta R}{\sqrt{\pi/2} \sigma R} \left( \frac{\sigma}{\beta} \right)^{-\alpha \sigma}}$$

(17)

By using [24]:

$$E_y(r, \phi) = BH_v^{(2)}(n_o kr) e^{-i \phi} \quad r > r_o$$

(18)
\[ E_y(r, \phi) = \frac{Bi}{\sqrt{\pi / 2}R} e^{\beta R \tanh^{-1} \left( \frac{\sigma}{R} \right)} e^{-\alpha R} e^{-jR\phi} \quad r > r_o \]  

(19)

And comparing it with [25]:

\[ E_y(x, z) = \left( \frac{2\omega \mu_o P}{\sqrt{\beta a(1 + (1/\sigma a))}} \right) \cos(ku) e^{-\sigma x} e^{i\sigma z} \quad x > a \]  

(20)

B can be determined as [25]:

\[ B = \left( \frac{2\omega \mu_o P}{\sqrt{\beta a(1 + (1/\sigma a))}} \right) \left( \sqrt{\pi / 2}R \right) e^{-\beta R \tanh^{-1} \left( \frac{\sigma}{R} \right)} e^{iR} e^{\sigma a} \cos(ku) \]  

(21)

Now before solving for the power loss coefficient, 2\( \alpha \), a few other equations need to be determined first. The first of these equations is the radiated power (\( S_r \)). Using the basic power equations as the basis, \( S_r \) can be found as [26]:

\[ S_r = -\frac{1}{2} \text{Re} \left\{ E_y H_y^* \right\} \]  

(22)

\[ S_r = -i|B|^2 \left( \frac{n_o \omega E_o}{2k} \right) H_v^2(n_o kr) H_v^{(2)}(n_o kr)^* \]  

(23)

Now that the only unknowns left are \( H_v^2(n_o kr) \) and \( H_v^{(2)}(n_o kr)^* \), the large argument approximation can be made [24]:

\[ H_v^{(2)}(n_o kr) = \frac{2}{\pi(n_o kr)} e^{-i(n_o kr)} e^{i(\pi/4)} e^{i(\pi/2)} \]  

(24)
Taking the derivative and conjugate gives:

$$
H_v^{(2)}(n_v kr)^* = \sqrt{\frac{2}{\pi}} \frac{e^{-i(\pi/4)} e^{-iv\pi/2}}{i e^{i(n_v kr)}} \left[ i e^{i(n_v kr)} \left( n_v kr \right)^{1/2} - \frac{1}{2} \left( n_v kr \right)^{3/2} e^{i(n_v kr)} \right]
$$  \hspace{1cm} (25)

Now that all the parameters are known, they can be plugged back into the \( S_r \) equation and the equation can be reduced to:

$$
S_r = |B|^2 \left( \frac{\omega \varepsilon_o}{k^2 \pi} \right)
$$  \hspace{1cm} (26)

By plugging in \( S_r \) and \( B \) into the power loss coefficient equation, which is the radiated power per unit length over the power through the waveguide [24]:

$$
2\alpha = \frac{(S_r)(r/R)}{P}
$$  \hspace{1cm} (27)

$$
2\alpha = \left( -\frac{\sigma^2 \mu_0 \varepsilon_o}{\beta k^2 a (1 + (1/\alpha a))} \right) e^{-2iR \tanh^{-1} \left( \frac{\sigma}{\beta} \right)} e^{i2\sigma R} e^{2\sigma a} \cos^2(\kappa a)
$$  \hspace{1cm} (28)

This equation solves for the power loss of a single mode bend in units of [1/\( \text{um} \)]. In order to make this loss more comparable with the simulation results, it must be turned into [dB/\( \text{um} \)] by using the following equation [24]:

$$
\text{Bending Loss [dB/um]} = -10 \log_{10} \left( e^{-2(\alpha_{\text{bend}})/\text{[um]}} \right)
$$  \hspace{1cm} (29)
2.2 Simulation and Results of Mode 0 Bending Loss

Using the previous equations, the bending loss for mode 0 was analytically calculated using the parameters in Table 2.1.

**Table 2.1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1.55µm</td>
</tr>
<tr>
<td>Polarization</td>
<td>TE</td>
</tr>
<tr>
<td>Background Index</td>
<td>1</td>
</tr>
<tr>
<td>Waveguide Width</td>
<td>0.45µm</td>
</tr>
<tr>
<td>Index Difference</td>
<td>0.8944</td>
</tr>
<tr>
<td>Radius of Curvature</td>
<td>1µm to 10µm</td>
</tr>
<tr>
<td>(b)</td>
<td>0.619</td>
</tr>
<tr>
<td>(\beta)</td>
<td>6.5394e6</td>
</tr>
<tr>
<td>(\kappa)</td>
<td>4.0258e6</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>5.1314e6</td>
</tr>
</tbody>
</table>

The results of the analytical calculations were plotted and simulations were performed for comparison. The simulations were designed in R-soft, which can be seen in Figure 3 and the necessary parameters were taken from Table 2.1. Time monitors were used to calculate the input and output power.

![Figure 3: R-soft design for testing bending loss on a standard bend.](image)

Using the equations below, the bending loss was calculated and turned into dB/um [25].

\[
P_{\text{out}} = P_{\text{in}} e^{-2\alpha z} \quad (30)
\]

\[
\text{Bending Loss [dB/um]} = -10\log_{10}\left(e^{-2(a_{\text{loss}})(1\mu m)}\right) \quad (31)
\]
After all the data was collected and plotted, the two sets of results were compared in Figure 4. It can be seen from the results that the analytical and simulation results match up very closely.

![Figure 4: Comparison of bending loss results for a mode 0 standard bend.](image)

2.3 Simulation and Results of Mode 1 Bending Loss

The next step was to perform the same calculations and simulations for mode 1. The previous analytical calculations used for TE0 are in general form and can therefore be used for TE1. The only changes needed are the parameters of the waveguide bend, which can be seen in Table 2.2.

<table>
<thead>
<tr>
<th>Table 2.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength = 1.55µm</td>
</tr>
<tr>
<td>Background Index = 1</td>
</tr>
<tr>
<td>Index Difference = 0.8944</td>
</tr>
<tr>
<td>b = 0.843</td>
</tr>
<tr>
<td>κ = 2.5843e6</td>
</tr>
</tbody>
</table>
Using these new parameters, the analytical calculations and simulations were once again determined. The results were plotted together for comparison (see Figure 5).

![Bending Loss](image)

**Figure 5:** Comparison of bending loss results for a mode 1 standard bend.

It can be seen from the results that the analytical and simulation results match up very closely. These results resemble that of the mode 0 results in Figure 4. The only difference is that the mode 1 bend has a slightly larger loss at each radius of curvature. A reasonable explanation can be determined for why mode 1 has more loss than mode 0. Before this explanation is given, it is important to note the reason is not directly due to the waveguide width. Even when mode 0 was sent through the mode 1 parameters, it still had a smaller radiation loss. The real reason why mode 1 had more loss was because as the wave travels around the bend, its energy begins to shift towards the outer edges causing these edges to be more confined. By referring to the previously mentioned Figure
1 and recalling that the outer wavefronts cannot travel fast enough to keep up with the inner wavefronts, it can be seen that the radiation loss occurs mainly at the outside of the bend. This means the original confinement of the wavefront before entering the bend plays the essential role in the bends loss. As can be seen in Figure 6 on the left, a multimode wavefront naturally has more energy towards the outer edge of the waveguide than a single mode wavefront (the Figures show an equal waveguide width). As the wavefront begins to turn around the bend (Figure 6 on the right), more energy is pushed out against the outer edges; hence, causing more loss for the mode 1 wavefront.

![Figure 6: Mode 0 & 1 wavefronts traveling through straight waveguide (left) and bent waveguide (right).](image-url)

**Chapter 3**

**3.1 Compact Mode Bends**

The focus for this project will be on three 90 degree planar waveguide bends. Their shape and structure allow them to have a smaller turn radius than standard curved bends. All three types of 90 degree bends will be examined and then compared with a standard curved bend. They include a resonant cavity bend, a single mirror bend, and a double mirror bend (see Figure 7) [2].
Figure 7: Sketch of resonant cavity bend (A), single mirror bend (B), and double mirror bend (C) [2].

The parameter “a” in Figure 7 is the radius of curvature for each of the designs. The parameter “d” in the mirror designs represents the new larger width of the midsection of the bend. The resonant cavity bend (resonator bend) was designed by using a low Q resonant cavity at the inner portion of the bend to create standing and traveling waves inside the cavity [2]. The addition of high index material to the inner portion of the standard design slows down the inner wavefronts. Recalling the theory from Chapter 2, the outer wavefronts moving around a bend must travel faster than the speed of the light to catch the inner wavefronts. Since this is not feasible, the reverse approach of slowing down the inner wavefronts can be achieved by adding high index material to the inner portion of the design. The resonator design also entails a 45 degree cut, which is used due to the fact that a traveling mode undergoes total internal reflection and is guided around the corner by the outer walls [27]. The addition of the cut also helps to slow down the outer wavefronts and ensure an even wavefront distribution at the output of the bend. In addition to the effect of the cavity resonance, the geometry of the structure also affects
the traveling waves through index-guiding [2]. After further investigation, it was determined that this index-guiding actually played a much greater role in the transmission than the cavity resonance; hence, the cavity was reduced until it evenly matched up with the input and output waveguides [2]. The resulting design was the single mirror (see Figure 7B). After experimentation with the single mirror, it was found that the outer sharp corners were causing loss [2]. To reduce this loss, the initial input angle was reduced and another cut was added to reduce the output angle. The resulting design was the double mirror (see Figure 7C). All of the designs shown in Figure 7 (excluding the dotted line shown on the double mirror bend) were created and studied by [2] using single mode. The following analysis will concentrate on testing these designs using multimode and then propose a newly optimized multimode design (see Figure 7: double mirror design with additional cut represented by dotted line). Before the multimode simulations can be performed, it is essential to check the method of analysis by simulating the designs using single mode and comparing the results to [2].

3.2 Mode 0

The four different types of bends will be simulated on R-soft using the optimized parameters given in [2]. These parameters are as follows:

\[ TE_0 \]
\[ n_i = 3.2 \]
\[ n_s = 1 \]
\[ n_o = 1 \]
\[ 2a = 0.2 \mu m \]
\[ \lambda = 1.55 \mu m \]
Table 3.1

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Radius of Curvature (a) in µm</th>
<th>Midsection Thickness (d) in µm</th>
<th>Angles in Degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend</td>
<td>0.5 – 2.0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Resonator</td>
<td>0.72</td>
<td>N/A</td>
<td>45</td>
</tr>
<tr>
<td>Single Mirror</td>
<td>0.74</td>
<td>0.366</td>
<td>45</td>
</tr>
<tr>
<td>Double Mirror</td>
<td>0.79</td>
<td>0.315</td>
<td>35/55</td>
</tr>
</tbody>
</table>

The R-soft CAD designs created using these parameters are given in Figure 8 (Note that for the standard bend, a = 0.72µm, the actual simulations vary this “a” from 0.5-2.0).

![Figure 8: R-soft CAD designs for all four geometries.](image)

After the geometries were created, the simulations were run with a small grid size of 0.01 um for accuracy. Being that R-soft uses finite difference time domain, the grid size determines the discrete points of the grid; hence, the smaller the grid size, the more accurate the results. However, there is a tradeoff between accuracy and time. Eventually the accuracy will only vary by a small percentage, but the simulation time will vary by
several hours. After several simulations were run with different grid sizes, it was determined that 0.01 um had a very high accuracy and a reasonable simulation run time. The accuracy was within 0.001% and the simulation time was only on the order of several hours. The stop time was set to 50, which was determined to be the point where the output hit steady state. Time monitors were used to collect the time average power at the input and output. A snapshot of the simulations for each of the designs is given in Figure 9 (Note that for the standard bend, a = 0.72 µm, the actual simulations vary this “a” from 0.5-2.0).

![Figure 9: Snapshots of the simulations for the four designs.](image)

Using the saved results from the simulations, the percentage of the transmission was calculated for each design by dividing the output power at steady state by the input power at steady state. The results for the three 90 degree designs were plotted along with the standard bend results for comparison (see Figure 10, left graph). The overall results
can also be compared with the results found from [2] (see Figure 10, right graph). It can be seen that the two sets of results closely match up with the exception of the resonator bend in which [2] did not attempt to examine. Despite the fact [2] did not show the results of the resonator design, it is still very important to show how its performance compares to that of the other three designs.

![Transmission of Circle Bend in Singlemode](image)

**Figure 10:** Comparison of results for transmission versus radius of curvature [6].

The results signify that at a given transmission, the three designs offer an equivalent transmission as the bend, but with the advantage of a smaller size. The best design appears to be the double mirror bend in which it offers a 99% transmission. When compared to the standard bend at 99% transmission, the radius of curvature is decreased by 13%. The similarity of the single mode results prove that the method of analysis (simulations) works. This method of analysis can now be used to simulate the designs using multimode.
3.3 Mode 1

Being that these designs have not been tested yet using multimode, all of the designs parameters have to be re-evaluated. The first step in doing this is to find the range of widths for the input and output waveguides so that the designs will support mode 1 (TE\(_1\)). The parameters and equations for \( V_{\text{cutoff}} \) are given as [25]:

\[
\begin{align*}
TE_0 \\
n_1 &= 3.2 \\
n_s &= 1 \\
n_o &= 1 \\
2a &= 0.2\mu m \\
\lambda &= 1.55\mu m
\end{align*}
\]

\[
V_{\text{cutoff}} = \frac{m\pi}{2} + \frac{1}{2} \tan^{-1}(\sqrt{\gamma}) \\
(32)
\]

For TE\(_1\): \( m \) is between 1 and 2. Plugging this into the above \( V_{\text{cutoff}} \) equation yields:

\[
\begin{align*}
V_{\text{cutoff}} &= \pi/2 \text{ at lower boundary} \\
V_{\text{cutoff}} &= \pi \text{ at upper boundary}
\end{align*}
\]

Plugging the above values into [25]:

\[
V_{\text{cutoff}} = \left(\frac{2\pi}{\lambda}\right)(a)\left(\sqrt{n_1^2 - n_s^2}\right) \\
(33)
\]

yields:

- Minimum width \( 2a = 0.255 \mu m \)
- Maximum width \( 2a = 0.510 \mu m \)
It was determined by experimentation that the maximum width was too large for the “d” parameter and that if the width was used, then the entire design would need changed. For this reason, the minimum width was experimentally tested, but the results showed that it was too unconfined to support TE₁ properly. In order to get proper confinement and not have to change the design a width in-between the maximum and minimum needed to be chosen. After experimentation, it was determined that this width should be about 0.4 µm. This new width was used in all of the designs and all of the other parameters were optimized around it. After a complete evaluation of the possible parameters and designs, it was determined that the following parameters in Table 3.2 were optimal for all of the designs.

Table 3.2

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Radius of Curvature (a) in µm</th>
<th>Midsection Thickness (d) in µm</th>
<th>Angles in Degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend</td>
<td>0.5 – 2.0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Resonator</td>
<td>0.94</td>
<td>N/A</td>
<td>45</td>
</tr>
<tr>
<td>Single Mirror</td>
<td>1.0</td>
<td>0.57</td>
<td>45</td>
</tr>
<tr>
<td>“New” Double Mirror</td>
<td>1.2</td>
<td>0.486</td>
<td>25/65 - 45 (0.09)</td>
</tr>
</tbody>
</table>

The only new addition to Table 3.2 is the 45(0.09) in the bottom right cell. This represents the third 45 degree cut, which was previously mentioned in this report and can be seen in Figure 7C as the dotted line. The 0.09 signifies that the height of the triangular region that was cut out was 0.09 µm.

The modified multimode R-soft CAD designs resemble the designs shown in Figure 7 with the exception of the newly sized parameters and the new 45 degree cut on
the double mirror. After the geometries were created, the simulations were once again run with a small grid size of 0.01 um for accuracy. The stop time was again set to 50, which was determined to be the point where the output hit steady state. Time monitors were once again used to collect the time average power at the input and output. A snapshot of the simulations for each of the designs is given in Figure 11 (Note that for the standard bend $a = 1.2 \, \mu m$, the actual simulations vary this “a” from 0.5-2.0).

![Figure 11: Snapshots of the simulations for the four designs.](image)

Using the saved results from the simulations, the percentage of the transmission was once again calculated for each design by dividing the output power at steady state by the input power at steady state. The results for the three 90 degree designs were plotted along with the standard bend results for comparison (see Figure 12). It can be seen that the pattern of the results resemble the pattern of the single mode results in Figure 10. All
three designs once again offer an equivalent transmission as the bend, but with the advantage of having a smaller size. The double mirror bend is also still the best design, but now it offers a 97.4% transmission. When compared to the standard bend at 97.4% transmission, the radius of curvature is decreased by 25%.

![Transmission of Circle Bend in Multimode](image)

**Figure 12:** Transmission versus radius of curvature for TE1 input in all four designs.

### 3.4 Mode 0 in Mode 1 Parameters

It can be seen that these designs once again outperformed the standard bend, but now in multimode. The final step was to keep the same parameters, but inject single mode (TE\textsubscript{0}) to see if the designs would be able to support both single mode and multimode (TE\textsubscript{1}). A snapshot of the simulations for each of the designs is given in Figure 13 (Note that for the standard bend, $a = 1.2 \, \mu m$, the actual simulations vary this “a” from 0.5-2.0)
Using the saved results from the simulations, the percentage of the transmission was once again calculated for each design. The results for the three 90 degree designs were plotted along with the standard bend results for comparison (see Figure 14). It can be seen that the results highly vary from the single mode and multimode results in Figures 10 and 12. The single mirror and resonator designs fail to outperform the standard bend; however, this is not the case for the double mirror bend. It competes with the standard bend design in which it offers a similar transmission of 99.6% at an approximately equivalent radius of curvature. It also has an output closer to single mode than the standard bend. This can be observed by looking at the simulations of the double mirror bend and standard bend in Figure 13. The output of the standard bend appears to be wavy, showing signs of mixed mode output. The output of the double mirror bend is not as wavy showing better signs of single mode. This proves that the new double mirror design once again outperforms the standard bend.
3.5 Results for Compact Mode Bends

There are a couple possible reasons why the single mirror bend and resonator bend did not perform very well with single mode. The first reason, which was already pointed out, is the wavy output field. The new design parameters caused the single mode to bounce back and forth throughout the turn causing loss and mixed modes at the output.

The second reason is due to the high index material. As previously mentioned, the high index material was added to the inner portion of the designs to slow down the inner wavefronts. For the single mode design, a specific amount of high index material was added to make sure the inner wavefronts slowed down just enough for the outer wavefronts to catch up and perfectly match up at the output. When the parameters changed to support TE\(_1\), the parameters were made larger; hence, more high index material was added to the design. The problem occurred because when the single mode was sent back through, there was too much high index material on the inner portion of the design and the inner wavefronts were slowed down too much causing an uneven
matching at the output; hence, causing loss. This explains why the new 45 degree cut on the double mirror design improved the single mode output transmission. When the new cut was added, it added another bend on the outer portion of the design, which slowed down the outer wavefronts enough to catch up with the inner wavefronts.

The 90 degree bends proved to be very advantageous over the standard bend design. When solely single mode or multimode was inputted into the structures, the new designs proved to have the advantage of a smaller size at a given transmission. The overall best design was the double mirror design with the additional 45 degree cut. The 45 degree cut improved the transmission by 4% over the original design. This design proved to outperform the standard bend when both single mode and multimode was sent in together.

Despite the various advantages of the designs, they do have several disadvantages. If high transmission is a necessity and size is not a factor, then the standard bend outperforms all of the new designs. The other big disadvantage for all of the new designs, with exception of the double mirror design, is that when both single mode and multimode was inputted into the designs, they failed to outperform the standard bend.

There is much work to be done in the future on the optimization of bends. Not only can the geometries and parameters for the designs covered in this report be further modified, but new geometries and materials can be explored. However, at this point in
time, it appears that the double mirror bend design outperforms all other bends and meets the goals of this project. It will therefore be accepted as the new optimized design.

Chapter 4

4.1 Introduction and Theory of Tapered Fibers

Integrated optics involves the miniaturization of bulk optical components to the chip scale. When dealing with the coupling between a waveguide and optical fiber the large size differences cause much of the power to be lost. A method for reducing this loss is coupling with a tapered single mode fiber. The coupling efficiency depends on the modal profile matching between the fiber and waveguide. An untapered fiber has large coupling losses due to the fact that the mode field diameter is poorly matched to the smaller mode profile of a rectangular waveguide [28]. A tapered fiber, on the other hand, is designed to have a better modal profile match to the mode profile of the waveguide. In order to optimize the coupling, specific parameters must be chosen for the fiber and waveguide. Using the materials in the lab, these parameters are as follows:

<table>
<thead>
<tr>
<th>Step Index, Single Mode Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode Field Diameter (MFD) = 9.3 ± 0.5µm</td>
</tr>
<tr>
<td>Cutoff Wavelength: λ_{cutoff} = 1260 ± 40nm</td>
</tr>
<tr>
<td>Core Diameter = 3.71µm</td>
</tr>
<tr>
<td>Temperature Operating Range = -65°C to 135°C</td>
</tr>
</tbody>
</table>

n_{cladding} = 1.46  
NA = 0.13  
n_{core} = 1.47
Rectangular Waveguide Structure

Height, \( h_{wg} = 2 \, \mu\text{m} \)    Width, \( w_{wg} = 2 \, \mu\text{m} \)
\( n_{wg} = 1.55 \)    \( n_s = 1.46 \)

The entire tapered geometry can be seen in Figure 15. Also shown is the gap spacing between the fiber and waveguide. In this analysis, this is assumed to be zero.

From the parameters given earlier, the core radius can be determined by the \( V \)-number equation, where \( \lambda_{\text{cut-off}} \) is given as 1260 nm [26]:

\[
V = 2\pi \frac{a}{\lambda_{\text{cut-off}}} \frac{a}{NA} = 2\pi \frac{a}{1260 \times 10^{-9}} \frac{0.13}{0.13} = 2.405 \tag{34}
\]
Assuming the cut-off $V$ (for a SMF) is 2.405, the radius, $a$, is found to be 3.71 µm. At the wavelength of interest, $\lambda_o = 1.55$ µm, the mode field diameter (MFD) is 9.5 µm. This energy contained in the MFD must be coupled completely into the rectangular waveguide for maximum efficiency. This can be determined by evaluation of the fiber coupling efficiency equation as [26]:

$$\eta = \left[\frac{4\beta_i^2}{(\beta_i + \beta_r)^2}\right] \frac{\int E_i(r,\phi)E_i^*(r,\phi)rdrd\phi}{\int E_i(r,\phi)E_i^*(r,\phi)rdrd\phi}$$

This equation shows how much power can be coupled from an incident mode field $E_i$ into a structure with a mode field of $E_i$ normalized by the power contained in both fields [26]. The integral terms describe an overlap integral and give an idea on how close the two fields appear: the closer the fields, the better the overlap. Assuming an equivalent MFD of the rectangular waveguide is close to its dimensions, it can be seen that much loss will occur with the coupling between an untapered fiber and the rectangular waveguide due to the great difference in these diameters. The point, therefore, of creating a tapered fiber is to transform the excited HE$_{11}$ mode of the SMF into the first TE mode of the rectangular waveguide. It can be assumed that the output of the taper should be single mode, also from the above equation; therefore, it is important to examine the number of modes with different final tapered radii.
A first-order approximation of the number of modes can be determined by assuming that the taper angle is very small. The number of modes, $N$, are approximated below [26] and also given in Figure 16:

\[
\begin{align*}
\text{For } V < 2.405 & \rightarrow N = 1 \text{ (due to cut-off)} \quad (36) \\
\text{For } V > 2.405 & \rightarrow N = \frac{4V^2}{\pi^2} \quad (37)
\end{align*}
\]

![Figure 16](image.png)

**Figure 16:** Graph of the changes in modes with respect to the changes of the cores radius.

As the radius, $a$, is increased past the core diameter of 3.71 μm, the cladding is present. Before this, the cladding is small and slowly increasing. When the fiber is small, it may be approximated as multi-mode; however, at some point when the cladding is large, the fiber must be single mode. It can be seen from Figure 16 that the tapered fiber is approximately single-mode at a diameter of around 1 μm. Using this as an approximation, simulations were further conducted using R-soft.
4.2 Tapered Fiber Losses

Looking at the power loss through the tapered fiber in Figure 17, it can be seen that there are very low losses and they are only slightly dependent on the taper angle.

![Figure 17: Power loss through tapered fiber.](image)

Looking at the power coupling loss at the interface in Figure 18, it can be seen that there is low loss only from roughly 0.5µm to 2µm. It can also be seen that the untapered fiber is very lossy and that the loss is not dependant on the taper angle.

![Figure 18: Power coupling loss through interface.](image)
Looking at the total power loss in Figure 19, it can be seen that the minimum loss is roughly around 2µm to 3µm. Once again, the taper angle does not have a significant effect and that untapered fiber can be seen as very lossy.

Figure 19: Total power loss from fiber and coupling.

The results for the total power loss at 2 degrees and the waveguide only at 2 degrees can be compared with each other and with work previously done [28]. It can be seen in Figure 20 that all of the results closely match up together.

Figure 20: Comparison of losses (simulation results on left / previous work from [28] on right.)
4.3 Causes of Loss in Tapered Fibers

In order to obtain an understanding of what is contributing to the losses shown in the previous section, the fields in the time and frequency domain can be examined. For the following simulations, the $E_x$ field will be the predominate field observed. Beginning with the poorly match tapered fibers and waveguides in Figure 21, it can be seen that the fibers have large MFD’s and their losses are very high. The tapered fiber with the diameter of 4µm has a loss of 0.8dB and the tapered fiber with the diameter of 12µm has a loss of over 3 dB.

![Figure 21: Coupling of waveguide and tapered fiber with diameters of 4µm (left) and 12µm (right).](image)

Now looking at a better matched waveguide and tapered fiber in Figure 22, it can be seen that its MFD matches up very well. The tapered fiber has a diameter of 2µm and only has a loss of 0.4dB.

![Figure 22: Coupling of a well matched waveguide and tapered fiber.](image)
Overall, it can be seen that tapering a fiber has a substantial effect on coupling loss. The optimization of the fiber was found to have a 3.5dB power loss difference. This occurred when the tapered fiber was in single mode. The taper angle (2 to 5 degrees) had a minimal effect on the power loss. The minimum power loss was found to be 0.4dB at a diameter of roughly 2µm to 3µm.

Chapter 5

5.1 Optimization of Data Acquisition Software

The final step is to optimize the data acquisition software, LabView. For this project some of the LabView programs, which collect the data from the test set-up, already exist. The only additional programs needed are the ones that control the power meter and laser. For future work, a virtual spectrum analyzer program and actuator program were also written. Each of these programs as well as their purposes and accuracy will be described in greater detail.

5.1.a Power Meter and Laser

The power meter and laser controller program were written in order to provide a more convenient means of use of the two devices for the user. The entire lab setup, which includes all of the equipment, is located inside an enclosure. Due to the high sensitivity of the equipment and importance of gathering very accurate data, this enclosure is used to protect all of the equipment from any unwanted outside environmental factors, such as dust or wind. Therefore, there is a great importance to have control of the equipment using the main computer, which is located outside the enclosure and communicates with
the equipment using GPIB. The LabView program, which is given in Figure 23, shows the front panel of the program.

![Figure 23: Front panel of the laser and power meter controller program.](image)

The functionality of the program described by label is given as follows:

1.) **Channel A – Power Meter Reading**: This box displays the power reading from channel A on the power meter.

2.) **Channel B – Power Meter Reading**: This box displays the power reading from channel B on the power meter.

3.) **Channel A**: This box displays the units for the Channel A - Power Meter Reading box (units in dBm or Watts).

4.) **Channel B**: This box displays the units for the channel B - Power Meter Reading box (units in dBm or Watts).
5.) Wavelength (um): This box displays the current wavelength reading on the laser.

6.) Power (dBm): This box displays the current power reading on the laser.

7.) Power Meter Screen (Dim and Undim): These two buttons will either dim or undim the screen on the power meter (used during testing to minimize light).

8.) Set Power Reading (Watts and dBm): These two buttons will set the units on the power meter to either Watts or dBm.

9.) Dim Laser Screen (Dim and Undim): These two buttons will either dim or undim the screen on the laser (used during testing to minimize light).

10.) Set power on laser to (+10dBm and -10dBm): These two buttons will either set the output power on the laser to +10dBm or -10dBm.

11.) Set lambda on laser to (1550nm): This button will set the output wavelength on the laser to 1550 nanometers.

12.) Enter Power: This box allows the user to type in a desired output power in dBm for the laser. After the desired power is typed in, the user can then push the enter button to set it on the laser (if the power is outside the limit of the laser, nothing will occur).

13.) Enter Lambda: This box allows the user to type in a desired output wavelength in nanometers for the laser. After the desired wavelength is typed in, the user can then push the enter button to set it on the laser (if the wavelength is outside the limit of the laser, nothing will occur).
14.) Laser Output (On/Off): This button will either turn the output of the laser on or off (if the LED turns green it indicates the laser output is on and if it is not green it indicates the laser output is off).

15.) Laser Locked (Locked/Unlocked): This button will either lock or unlock the laser keys for safety reasons (upon locking and unlocking, a dialog box will appear for the user to type in the password).

5.1.b Virtual Spectrum Analyzer

Just as the power meter and laser program, the virtual spectrum analyzer was also written in order to provide a more convenient means of use of the two devices for the user. This program not only controls some of the functions of the laser, but it also provides a graph of the output power of the device being tested versus the lasers output wavelength. The LabView program, which is given in Figure 24, shows the front panel of the program.

![Figure 24: Front panel of the virtual spectrum analyzer program.](image)
The functionality of the program described by label is given as follows:

1.) Wavelength (nm) (box and “SET” button): This box allows the user to type in an output wavelength in nanometers for the laser. After the wavelength is typed in, the user can then push the “SET” button to set it on the laser (if the wavelength is outside the limit of the laser, nothing will occur).

2.) Power (dBm) (box and “SET” button): This box allows the user to type in a desired output power in dBm for the laser. After the power is typed in, the user can then push the “SET” button to set it on the laser (if the power is outside the limit of the laser, nothing will occur).

For the following numbers 3-10, nothing will occur until the “START DATA COLLECTION” button is pushed. After data collection is completed, a save prompt will occur (see red print on top right of Figure 24).

3.) Starting Wavelength (nm): This box allows the user to type in a specified starting wavelength in nanometers (first data point during test).

4.) Increment (nm): This box allows the user to type in a specified increment in nanometers which will be used from start to stop (used for data collection).

5.) Stopping Wavelength (nm): This box allows the user to type in a specified stopping wavelength in nanometers (last data point during test).

6.) Number of points for averaging: This box allows the user to type in the amount of power reading points that will be collected and averaged on each data collection point (the final average will be displayed on the graph).
7.) Dwell time: This box allows the user to specify the wait time between each of the increments.

8.) SPREC (DC Sample Precision Select): This box allows the user to pick the precision of the power meter when collecting data points (setting can be on 4,096 for low precision or 20,000 for high precision).

9.) Freq (Hz) (DC Sample Frequency Select): This box allows the user to pick the frequency of the power meter when collecting data points (can be set to 0.001 to 25 when SPREC is set to 20,000 or can be set to 0.001 to 1,000 when SPREC is set to 4,096).

10.) Power (graph): This graph displays the averaged power (watts) as the wavelength (nm) is incremented.

11.) Current Wavelength: This box displays the current output wavelength on the laser in nanometers.

12.) Power Reading: This box displays the current power meter reading in watts.

13.) Turn laser ON (with indicating green LED): This button will turn the output of the laser on and indicate the action with a green LED.

14.) Turn laser OFF (with indicating red LED): This button will turn the output of the laser off and indicate the action with a red LED.

5.1.c Actuators

Just as the other programs, the Actuator program was also written in order to provide a more convenient means of use of the two devices for the user. This program (the largest of the three) is designed to move the actuators in a certain pattern while collecting data. The two actuators (Right Actuator - RA and Left Actuator – LA) are each
connected to an optical fiber and are located at the output of the device being tested. After the fiber collects the outputted light, the polarization of one of the fibers is changed and the two are coupled together. The final coupled fiber is then sent to the photodetector and power meter for data collection. The actuators movement and position can be controlled by the program. Each actuator has two possible axis movements. Both actuators can move either toward or away from each other causing the fibers to either come closer together or spread apart at the output (RA-Axis 1 and LA-Axis 1); one of the actuators can move up or down, raising the fiber above or below the device (RA-Axis 2); and the other actuator can move forward or backward, causing the fiber to move toward or away from the device (LA-Axis 2). Starting close together and using Axis 1, the fibers are moved away from each other in increments. At each increment, the LA-Axis 2 is used to slowly move the fiber away from the device and data is recorded. After the data is recorded, the fiber is moved back to its original position using the LA-Axis 2. This step can be repeated as many times as the user chooses (The data taken from each iteration is then averaged together for a final result.) After all of the iterations are completed, the next increment is made and process repeats itself. The data obtained at each increment is displayed live on the graph on the front panel and is also stored in an array. At the end of the program, a prompt will appear and the user has the choice to save all of the data. The reason for obtaining such data is that it shows how many modes are in the phase fronts that are outputted from the device. This can be helpful in finding things such as interference patterns at certain distances. The only other main function of this program is the sweep function. This function, which can be seen in the bottom right of Figure 25, allows the user to sweep a fiber across the output and record the power. This can be
useful in helping the user find the center of the output of the device. The LabView program, which is given in Figure 25, shows the entire front panel of the program.

Figure 25: Front panel of the actuators controller program.

The functionality of the program described by label is given as follows:

The following numbers 1-3 also apply to LHS Axis 2 / RHS Axis 1 / RHS Axis 2.

1.) Starting position for LHS Axis 1 (mm): This box allows the user to manually type in a position in millimeters for the LHS Axis 1.

2.) Set LHS Axis 1 (Set to current position): This button takes the current position of the LHS Axis 1 and writes it in the “Starting position for LHS Axis 1 (mm) box.”
3.) Change LHS Axis 1 (Change to New Position): This button actually sets the LHS Axis 1 to whatever position is typed in the “Starting position for LHS Axis 1 (mm).

For the following numbers 4-10, nothing will occur until the “START TAKING DATA” button is pushed.

4.) Number of data taking positions: This box allows the user to choose the amount of positions that will be used on Axis 1 to collect data.

5.) Increment for each actuator on Axis 1 (mm): This box allows the user to choose the increment for each actuator on Axis 1 in millimeters.

6.) Iterations of data collection for averaging: This box allows the user to choose how many data collecting iterations will be performed on LA-Axis 2 and then averaged.

7.) Velocity of data collection (unit/sec): This box allows the user to choose the velocity in which the LA-Axis 2 collects its data.

8.) SPREC (DC Sample Precision Select): This box allows the user to pick the precision of the power meter when collecting data points (setting can be on 4,096 for low precision or 20,000 for high precision).

9.) Freq (Hz) (DC Sample Frequency Select): This box allows the user to pick the frequency of the power meter when collecting data points (can be set to 0.001 to 25 when SPREC is set to 20,000 or can be set to 0.001 to 1,000 when SPREC is set to 4,096).
10.) Number of data collection points: This box allows the user to choose how many data collection points there will be for LA-Axis 2 iteration.

11.) Start logging / Reset / Stop logging: These buttons allow the user to start logging, reset, or stop logging data from the power meter onto the power graph before the “START TAKING DATA” button is even pushed.

12.) Power (graph): This graph displays the averaged power for each of the samples taken at a position when the LA-Axis 2 iterations are completed.

13.) Visibility (graph): This graph displays the visibility for each position on Axis 1. It is calculated using (max-min)/(max+min) from the outputted averaged power data, which is also being displayed in the “power (graph).”

For the following numbers 14-18, nothing will occur until the “Sweep (Start)” button is pushed.

14.) Actuator (LHS/RHS): This button allows the user to choose which actuator will be used to perform the sweep.

15.) Starting position (mm): This box allows the user to choose the starting position for the sweep in millimeters.

16.) Increment (mm): This box allows the user to choose the increment from start to stop in millimeters.

17.) Stopping position (mm): This box allows the user to choose the stopping position for the sweep in millimeters.

18.) Power (graph): This graph displays the power for each position from start to stop.
5.2 Accuracy

Due to the delay of the computer and cable transmission, research was conducted to find out the true accuracy and speed of LabView when data was being collected. To see this, data was taken directly from the power meter without storing it on the power meters buffer. A wait function was used in the program to set the frequency and ensure the data was being received. To test the accuracy of LabView, a specific wait function (millisecond multiple) was set and 3000 data points were collected. This process was repeated for a wide range of millisecond multiples. The timing of the data points for each millisecond multiple were then turned into frequencies. The average values and standard deviations of these frequencies were then calculated and plotted versus their millisecond multiple. The figure on the left in Figure 26 shows the Average value of frequency versus the millisecond multiple (speed of the data collection). The figure in the right in Figure 26 shows the comparison of the results with the theoretical results (1/millisecond multiple) that should have been obtained. It can be seen that the approximation almost exactly matches the average values in the range of ~22ms to 55ms. Any time before 22ms is the error due to the speed of the computer and cable transmission.

Figure 26: Frequency (speed) vs. millisecond multiple (left). Comparison of frequency results with theoretical results (right).
Figure 27 shows the standard deviation of the frequencies (accuracy) versus their millisecond multiple. It can be seen that the same error is occurring at lower millisecond multiples. Once again, this error is due to the speed of the computer and cable transmission. Also, what can be seen is that there is a tradeoff between speed and accuracy. The smaller millisecond multiples have a faster data collection rate, but worse accuracy; whereas, the larger millisecond multiples have a slower data collection rate, but better accuracy.

The buffer stores the recorded powers on the internal buffer of the power meter until the data collection is over. The computer then pulls the data off the buffer; hence, reducing the amount of time trying to send the data through the cable. Despite the fact that the buffer is a faster means of recording data, it still has a tradeoff between speed and accuracy. When the buffer is set to high precision (20,000) it can only collect data at a frequency of 0.001 Hz to 25 Hz, but when it is set to low precision (4096) it can collect data at a frequency of 0.001 Hz to 1000 Hz. Even though the buffer is a better means of collecting data, it is still important to know the limits of LabView without it.
Conclusion

Integrated optics is a very vast and complex technology. Research is being conducted to optimize its various devices and testing procedures. When attempting to study integrated optics, it is very important to get a feel for the overall process. This research accomplished that task by breaking down the larger project into smaller and more focusable pieces.

The first and most important piece of the project was the optimization of the bend and the study of its losses. Through analytical calculations and simulations, it was proved that mode 1 had a larger bending loss (about double) than mode 0. The reason for this is due to the different mode confinements of mode 0 and 1. Multimode wavefronts are less confined than single mode wavefronts, causing them to shift more energy to the outer edges of the bend; hence, having more energy radiated around the turn. Taking this theory into consideration, research was conducted on three different types of bends. It was found that the new “double mirror” design outperformed the standard bend and met all of the original design goals. These goals included: a minimum size, maximum efficiency, and capability to support both single mode and multimode. When a multimode input was sent into the double mirror design with the multimode parameters, its efficiency equaled that of the standard bend, but it had a 25% smaller radius of curvature. When a single mode input was sent into the double mirror design with the multimode parameters, its efficiency and size approximately equaled that of the standard bend. Despite this similarity, the new double mirror design still outperformed the standard bend because its output appeared to be more single mode then the standard bends output.
The second piece of this project was to optimize the coupling between an optical fiber and rectangular waveguide. The results showed that a tapered single mode fiber greatly outperformed an untapered fiber. The main reason why this was found to be true was that the MFD of the tapered single mode fiber matched up better with the rectangular waveguide than the MFD of the untapered fiber. The taper angle was found to not play a significant role in the loss and the maximum difference in power loss between the tapered and untapered fiber was found to be 3.5 dB. The minimum power loss by the tapered fiber was found to be approximately 0.4 dB at a diameter of roughly 2 µm to 3 µm.

The third and final piece of this project was the optimization of the data collection and testing equipment. Knowing the importance of having user friendly test equipment, each program was created with the ability to be understood by the first time user. This user friendly interface has been proven due to the fact that since the program has been finished, it has been used in the lab as the primary control over the equipment. All the functions of the programs have been tested and proven to run correctly.

When dealing with any future work on this project, the first task would be to fabricate and test the new double mirror bend using the optimized software. The next task would be to try to create new devices using the bend, such as a ring resonator. The new bend can even be tested to see if it offers any new coupling advantages. The last and most difficult future task focuses on the design parameters. The size of the designs structure in this project was based on specific parameters (such as indices and wavelength) to prove that such a structure could be optimal. If the parameters were to change, the design would
not work as efficiently and the structure would need changed (more or less high index material / more or less mirrors). Therefore, it would be very important to attempt to recreate the designs structure with different parameters and find the relationship between the parameters and the structure itself.

In summary, optimization is a key factor in integrated optics. It is not only important to keep updated on the continuous research occurring in this field, but it is also important to keep an open mind and try to improve on what has already been accomplished. Even the smallest advances are important changes because they will have a large impact on the overall field of study. Despite the importance of new technologies and advancements, it is very important to optimize the technologies that already exist. By keeping costs at a minimum, flexibility at a maximum, and efficiency at an all time high, the widespread use of integrated optics will continue to grow for many years to come.
References


