Properties Of High Energy Laser Light Transmission Through Large Core Optical Cables

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PROPERTIES OF HIGH ENERGY LASER LIGHT TRANSMISSION THROUGH LARGE CORE OPTICAL CABLES

by

CHRISTOPHER KENNEDY
B.S Rose-Hulman Institute of Technology, 2008

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in CREOL - College of Optics & Photonics at the University of Central Florida Orlando, FL

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Major Professor: Michael Bass
ABSTRACT

Laser induced damage is of interest in studying the transmission of large amounts of optical energy through step-index, large core multimode fibers. Optical fibers often have to be routed around objects when laser light is being transmitted between two locations which require the fiber to bend into a curve. Depending on how tight the bend is, this can result in transmission losses or even catastrophic damage when the energy density of the laser pulse exceeds the damage threshold of silica glass. The purpose of this study is to:

- Establish a minimum bend radius that would allow high energy (GW/cm²) to be transmitted through multimode fiber.

- Evaluate unique fiber routing configurations including loops, 180° bends, and S-bends.

- Develop optical modeling simulations backed with experimental data that can serve to predict critical areas for future systems.

Waveguide theory predicts that light traveling through a bend will form whispering-gallery modes that propagate through total internal reflection bounces along the inside of the outer edge of the bend. This is critical since in these locations the energy density of the light will increase significantly, raising the potential of laser damage, nonlinear effects, and transmission losses. This loss is especially problematic when two 90° bends going in opposite directions are in close proximity to each other, forming an ‘S-bend’. Light that is grouped along the outer edge going through the first bend will enter the second bend at a sharper angle which causes much high transmission losses and raises the possibility of failure.
Models using R-Soft BeamProp and Zemax were developed to study transmission losses, investigate light interactions at critical areas, and predict under which conditions laser damage would occur. BeamProp presents a clearer view of the modal distribution of light within the core of the fiber and is used to analyze how a plane wave with a Gaussian intensity distribution excites the fiber modes. Zemax provides a tool to perform non-sequential ray tracing through the fiber cable and stray light analysis within the core and once the light exits the fiber. Intensity distributions of the cross sectional area of the fiber shows the whispering gallery modes forming as the light propagates around bends and disburses as it propagates afterwards.

It was discovered using R-Soft that if the separation distance between bends in an S-bend is approximately 3 mm there exists a condition where maximum transmission occurs. For 365 µm diameter core fiber it was calculated that the difference in output power could be as high as 150%. This was initially completely unexpected; however ray tracing using Zemax was able to verify that this distance allows the light to transition so that it enters the 2nd bend at the optimal angle to enter the whispering gallery mode. Experiments were performed that validated the models’ predictions and images were captured clearly showing the spatial distribution shift of the light within the core of the fiber.

Experiments were performed to verify light grouping together to form whispering gallery modes as predicted by Zemax. Microscope images were taken as a function of distance from various bends to observe the periodic nature in which the laser light fills up the fiber. Additionally, a configuration was setup to examine stimulated Brillouin scattering and determine the onset of laser damage in the fiber. Fibers were tested as a function of bend radius and number of shots
and recommendations for future systems were made. Lastly, mechanical failure tests were performed to determine the relationship between stress placed on the fiber through bending and fiber lifetime in a static environment. This allowed a minimum safe bend radius to be calculated for a 30 year lifetime that agreed with previous calculated values.
ACKNOWLEDGMENTS

First of all I would like to thank my advisor, Dr. Michael Bass, for providing support and guidance throughout my time at CREOL. His knowledge and insight has been essential in successfully completing this work.

I would like to recognize the hard work and dedication of the Lasers, Spectroscopy, and Modeling group at CREOL, their efforts were fundamental in achieving these results. Amanda Chatterton for her assistance with the ray tracing software Zemax, Felix Tan and Dr. Scott Webster for their labors obtaining experimental data, and Matt Suttinger for his time spent modeling the stress in bent fibers using COMSOL. Additionally, Dr. Ali Gordon provided much needed support in measuring the mechanical properties of the fiber optic buffer.

Completing this project has given me a deeper appreciation for the engineers and scientists who have come before me. The journal articles and reports written by Dr. Robert Setchell at SNL and Paul Klingsporn at KCP provided a strong foundation for this work. The dedicated work of Gregg Morelli and Tanner Vaughn helped me form the initial idea for completing this work. The logistical support of Maxine Pennington and Nicole Schiedel made the technical fellowship much easier. Lastly, the mentoring provided by Jim Mahoney helped remind me of the excitement that science can instill.

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<th>Definition</th>
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<tbody>
<tr>
<td>ASAP</td>
<td>Advanced Systems Analysis Program</td>
</tr>
<tr>
<td>BPM</td>
<td>beam propagation method</td>
</tr>
<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>cm</td>
<td>centimeter ( (= 10^{-2} \text{ m}) )</td>
</tr>
<tr>
<td>CAD</td>
<td>computer-aided design</td>
</tr>
<tr>
<td>cw</td>
<td>continuous-wave</td>
</tr>
<tr>
<td>FM&amp;T</td>
<td>Federal Manufacturing and Technology</td>
</tr>
<tr>
<td>F</td>
<td>fluorine</td>
</tr>
<tr>
<td>FWHM</td>
<td>full width at half maximum</td>
</tr>
<tr>
<td>GHz</td>
<td>gigahertz ( (= 10^9 \text{ Hz}) )</td>
</tr>
<tr>
<td>GPa</td>
<td>gigapascal</td>
</tr>
<tr>
<td>GW</td>
<td>gigawatt ( (= 10^9 \text{ W}) )</td>
</tr>
<tr>
<td>HeNe</td>
<td>helium-neon</td>
</tr>
<tr>
<td>Hz</td>
<td>hertz</td>
</tr>
<tr>
<td>OH⁻</td>
<td>hydroxide</td>
</tr>
<tr>
<td>J</td>
<td>joule</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>kpsi</td>
<td>kilo-pound per square inch</td>
</tr>
<tr>
<td>LANL</td>
<td>Los Alamos National Laboratory</td>
</tr>
<tr>
<td>LP</td>
<td>linearly polarized</td>
</tr>
<tr>
<td>MPa</td>
<td>megapascal</td>
</tr>
<tr>
<td>µm</td>
<td>micrometer, micron ( = 10^{-6} m)</td>
</tr>
<tr>
<td>mJ</td>
<td>millijoule ( = 10^{-3} J)</td>
</tr>
<tr>
<td>mm</td>
<td>millimeter ( = 10^{-3} m)</td>
</tr>
<tr>
<td>mW</td>
<td>milliwatt ( = 10^{-3} W)</td>
</tr>
<tr>
<td>nm</td>
<td>nanometer ( = 10^{-9} m)</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>neodymium-doped yttrium aluminum garnet</td>
</tr>
<tr>
<td>NA</td>
<td>numerical aperture</td>
</tr>
<tr>
<td>ps</td>
<td>picosecond ( = 10^{-12} s)</td>
</tr>
<tr>
<td>SNL</td>
<td>Sandia National Laboratory</td>
</tr>
<tr>
<td>SVEA</td>
<td>Slowly-Varying-Envelope-Approximation</td>
</tr>
<tr>
<td>SBS</td>
<td>stimulated Brillouin scattering</td>
</tr>
<tr>
<td>TE</td>
<td>transverse-electric</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>TM</td>
<td>transverse-magnetic</td>
</tr>
<tr>
<td>W</td>
<td>watt</td>
</tr>
<tr>
<td>WGM</td>
<td>whispering-gallery modes</td>
</tr>
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1. INTRODUCTION

1.1 Research Motivation

It is well known that laser damage is possible when the energy density of a beam exceeds the bulk damage threshold of the material that is being transmitted through. This can be an issue when sending high peak power laser light through large core (365µm diameter) fiber optics. Time and effort has been spent on optimizing the front face of the optical fiber through advanced polishing schemes and even using millimeter long homogenous glass end caps. Another known area of concern for our applications was the static survivability of bent fiber cables. All fibers will fail at some point based upon the strength of the fiber and the stresses on the material by the environment. Testing was performed using fiber pull testing and bend testing to correlate the bend radius that a fiber experiences to its survivability. A bend radius of only a couple of mm has been shown to cause fiber of interest to us to break instantly, whereas a bend radius of several cm might last decades.

It was known that a degree of margin would need to be built into any minimum bend radius recommendations to account for variations in the strength of different fiber lots. However, it was surprising when catastrophic damage occurred in the laboratory when sending laser light through bends which were predicted to survive in static for a 30-year lifetime. One particular routing setup caught our attention when the light passed through a bend but then proceeded to cause damage when going through a 2nd bend routed in the opposite direction shortly after. Until that point, it had been assumed that if it was possible for the light to travel through a single bend then it would also be possible to make it through any number of similar bends.
Optical modeling programs ASAP and Zemax had been used to optimize the output and injection efficiency of the laser into the fiber, but until now had not been applied to the fiber routing. It was determined that developing a comprehensive fiber simulation was necessary in order to fully understand what was occurring for different geometries. Furthermore, while bend testing and pull tests often take weeks and sometimes years to complete, models can often provide useful data within hours or days.

A literature search led us to conclude that there existed two widely accepted ways to go about modeling large core optical fibers – ray tracing software to provide light pipe analysis and beam propagation method for electromagnetic wave investigations. It was decided that both would be employed and would be compared against experimental results. This allowed us to assess the performance of each software package and also evaluate different aspects of the light propagation through the fiber.

1.2 History

Laser damage studies were performed in large-diameter, step-index, multimode fibers in the early 1990’s by Setchell at Sandia National Laboratories (SNL) [1][2][3]. An Nd:YAG Q-switched laser was used to subject fibers to a test sequence of increasing energy densities until damage was observed or a maximum transmission of 80 J/cm² was reached. Of particular interest was the surface properties of the end face of the fiber and several different fiber polishing methods were varied for optimal performance. It was noted that areas where the fiber was placed under high static stresses due to the fixturing or bends in the fiber were more likely to experience
transmission failure. Damage was also observed within the first several millimeters of the entrance face due to the laser injection geometry and the mode structure of the laser.

The spatial variations in the laser itself were corrected for by adding two 25 cm loops in the fiber such that any internal reflections were homogenized and any effect of the mode structure of the beam would be negligible. Additionally, to minimize damage at the front face a “laser-conditioned” fiber was first injected into ahead of the test fiber, as shown in Fig. 1. The conditioned fiber used had a 600 micron diameter core of high-OH− fused silica with a 30 micron thick F-doped silica cladding with a 0.11 numerical aperture (NA). A 50-mm focal length lens was situated such that the spot size of the beam was 200 µm at the focal plane and expanded to 480 µm in diameter 5 mm downstream at the entrance face of the fiber. Thus, the beam was expanding and had an 80% fill factor at the fiber. Two lenses were used to inject the output of the conditioned fiber into the test fiber to produce a demagnification of 2. The test fiber used had a 400 micron diameter core of high-OH− fused silica with a 20 micron thick F-doped silica cladding with a 0.22 NA, which allowed efficient coupling from the 0.11 NA conditioning fiber.
Figure 1- Laser damage configuration used at SNL [3].

Damage experiments were performed on sets of 20 fibers consisting of different mechanical and CO₂ laser polishing methods. Each fiber was subjected to a series of single pulses with the energy being increased on successive pulses. Testing was performed until damage was detected at which point many of the fibers experienced a plasma-forming breakdown on the entrance face prior to permanent damage occurring. Only a small fraction of the laser energy would transmit when breakdown was first observed on a fiber, however the transmission would often return to normal for subsequent shots. Usually, the fiber would survive for several additional shots until persistent breakdown occurred. Results of the mechanical polished fibers is presented in Fig. 2,
showing both the procedure followed for each fiber as well as the detected energy transmission for both initial fiber breakdown (A) and catastrophic damage (B).

Figure 2- Injection energy procedure and laser damage results [3].

This experiment was repeated for fiber wrapped around a 7.6 cm and 5.1 cm diameter loop resulting in a 100 kpsi peak stress along the fiber path. The transmitted energy results indicated that initial breakdown and permanent damage occurred more frequently at higher energies, however there was not a significant impact on the onset of these occurrences. Therefore, it is likely that the fiber could survive through a much tighter bend.

Figure 3- Stress placed on fibers through 7.6 cm and 5.1 cm bend and transmission results [3].
Optical fiber strength tests were performed under applied tensile stress and bending stress by Klingsporn at Honeywell Federal Manufacturing and Technology (FM&T) in order to extrapolate a minimum fiber bend radius for a 30-year lifetime [4]. The failure of a fiber cable under tensile stress is dependent on the largest flaw in the sample, as shown in Fig. 4. For example, a fiber with a 1 micron crack would fail when it underwent an 80 kpsi stress. Surface cracks within the fiber are dependent on the manufacturing processes when drawing the fiber. Defects from manufacturing can occur due to the quality of materials used – including the fiber preform and coatings and buffers that are applied, the quality control of the drawing process, and the environment in which it takes place.

Figure 4- The largest fiber flaw dictates the stress the fiber can withstand [4].

The optical fiber industry has established a standard set of test procedures for testing drawn fiber by generating statistical distributions of the defect distribution in a sample lot based on its initial strength. [5]. Many fibers of a certain length undergo pull testing at a fixed strain rate and
increasing tensile strength until failure occurs. It is then possible to apply Weibull statistics to the data in order to produce a plot showing the probability of cumulative failure versus the stress level where failure occurred [6]. A Weibull plot showing the probability of a fiber breaking versus the breaking stress of the fiber is shown in Fig 5. It consists of three regions: region I in which failure caused by large flaws from proof tests performed after manufacturing, region II in which failure is due to flaws as a result of manufacturing and handling, and region III in which failure is the result from of small intrinsic defects in the surface of the silica glass. The slope of the distribution in region III along with the cumulative failure probability of 50% is a common figure of merit for characterizing a fiber lot. Typically a high quality fiber will have a region III that extends into probabilities less than a percent, a slope greater than 100, and its 50% probability of failure greater than 700 kpsi.

Figure 5- Weibull plot showing probability of failure as a function of breaking stress [4].
It was discovered by Morelli at Honeywell FM&T that in certain situations optical fibers would survive mechanical routing and temperature cycling, but would fail under these conditions while transmitting high energy laser light (1.6 – 2.0 GW/cm\(^2\) in the core of the fiber) [7]. One particular concern was in routing situations where an s-bend would allow the laser light to successfully pass through the first bend but cause catastrophic damage on the outer edge of the second bend, shown in Fig. 6.

![S-bend routing showing catastrophic damage in the outer edge of the second bend](image)

Figure 6- S-bend routing showing catastrophic damage in the outer edge of the second bend [7].

This unexpected failure was concerning since it is imperative that these optical fibers survive mechanical routings and transmit laser energy without failing. Up until this point, mechanical performance was the primary method of making minimum bend-radius and lifetime predictions. In order to improve reliability estimates for fiber routing requirements it was decided that laser light transmission should be evaluated through fiber configurations of interest, with special
attention to performance through bends. Furthermore, modeling should be employed to improve
the fidelity of using optical fibers in system platforms.
2. THEORETICAL BACKGROUND

2.1 Beam Propagation Method

The beam propagation method (BPM) is a computational technique used to solve the time-harmonic solution of the Helmholtz equation. Unlike ray tracing techniques, which use geometrical optics to model an electromagnetic field using a large number of rays, BPM is based on Maxwell’s equations which allow much greater accuracy for waveguide analysis. The computation time required to accurately model the propagation of a wave is very long for distances much longer than the wavelength of light. BPM can compensate for this by solving a series of approximate differential equations with the only first order derivative along the waveguide axis (the z direction). This series can be treated as initial value problems involving only the spatial variable z and does not require a temporal variable. The initial electromagnetic field distribution in each plane is calculated using the resultant fields in the previous plane. Modeling using a computer program allows a series of loops to be configured with an incremental step size along the waveguide axis [8]. The BPM simulations can be used to calculate using both the electric and magnetic fields, which will give the same results.

There are three accepted methods of calculating BPM: the full-vectorial BPM which takes into account the full vector properties of the waveguide modes, the semivector BPM which accounts for polarization but neglects coupling between $E_x$ and $E_y$, and the scalar BPM where both the polarization and cross coupling is ignored [9]. The full-vectorial method requires much longer computational times, but it is able to model small variations in the refractive index over the transverse dimension which is required for waveguide analysis of fiber optic cables through
bends. Therefore, only this method will be explored in depth due to its wider nature of applications.

The BPM equations can be numerically solved using the fast Fourier transform method, the finite-element method, or the finite-difference method. These methods are necessary since solving for the partial differential equations are so complicated that it would be impracticable to fine their solutions using purely analytical means. The fast Fourier transform computes the discrete Fourier transform solution and was widely used to design optical waveguides until the finite-difference method was developed. It is no longer used as often due to its much longer computational times, poor analysis at boundaries, and its inability to take into account polarization effects [10]. The finite-element approach finds approximate solutions for boundary value problems and uses the calculus of variations in order to minimize the error function. It requires much longer computational times and is therefore usually only used in situations where the photonic structure is complex due to its flexibility in mesh design. The finite-difference technique approximates solutions to the differential equations by discretizing a function on a grid and calculating the difference between adjacent points on the grid. This method introduces some error through round-off and truncation error; however keeping the step size between points to a minimum can minimize this.

The finite-difference full-vectorial beam propagation method is the most efficient process to solve the modes of a waveguide with a high index variation in the transverse direction, such as a bent large diameter core optical fiber. The BPM equations can be solved by using the vector
wave equation which is derived from Maxwell’s equations in the frequency domain, shown in Eq. (2.1) – (2.4).

\[ \nabla \times E = -i\omega \mu_0 H \quad (2.1) \]

\[ \nabla \times H = i\omega \varepsilon_0 n^2 H \quad (2.2) \]

\[ \nabla \cdot n^2 E = 0 \quad (2.3) \]

\[ \nabla \cdot H = 0 \quad (2.4) \]

The time-harmonic electric and magnetic field for the vector wave equation can then be derived for a linear isotropic medium, where \( n(x,y,z) \) is the index of refraction and \( k_0 = \frac{2\pi}{\lambda_0} \) is the wave number in a vacuum, shown in Eq. (2.5) and (2.6).

\[ \nabla \times \nabla \times E = \nabla \nabla \cdot E - \nabla^2 E = n^2 k_0^2 E \quad (2.5) \]

\[ \nabla \times \nabla \times H - n^2 k^2 H - \frac{1}{n^2} \nabla n^2 \times \nabla \times H = 0 \quad (2.6) \]

The wave equations are the foundation for the BMP simulations. Using either the electric or magnetic formula will reach an identical result, therefore only the electric will be examined. It is possible to use the curl of the curl identity, shown in Eq. (2.7), to describe the transverse components of Eq. (2.2) and (2.3) to yield Eq. (2.8) and (2.9).

\[ \nabla \times \nabla \times = \nabla \nabla \cdot - \nabla^2 \quad (2.7) \]
\[ \nabla^2 E_t + n^2 k^2 E_t = \nabla_t \cdot \nabla^2 E_t + \frac{\partial E_z}{\partial z} \quad (2.8) \]

\[ \nabla_t \cdot n^2 E_t + \frac{\partial n^2}{\partial z} E_z + n^2 \frac{\partial E_z}{\partial z} = 0 \quad (2.9) \]

It can be assumed that the refractive index is slowly varying along the \( z \)-direction, especially if the step size is chosen to be small, which allows the \( \frac{\partial n^2}{\partial z} E_z \) term to be ignored. This allows the change in the electric field along \( z \) to be calculated in Eq. (2.10) and then substituted into the transverse component shown in Eq. (2.8) to result in eq. (2.11).

\[ \frac{\partial E_z}{\partial z} \approx \frac{\nabla_t \cdot n^2 E_t}{n^2} \quad (2.10) \]

\[ \nabla^2 E_t + n^2 k^2 E_t = -\nabla_t \cdot \nabla \ln n^2 \cdot E_t \quad (2.11) \]

The transverse components shown in Eq. (2.11) can be decomposed in the following equations given in Eq. (2.12) and (2.13).

\[ \nabla^2 E_x + n^2 k^2 E_x = -\frac{\partial}{\partial x} - \frac{\partial \ln n^2}{\partial x} E_x - \frac{\partial}{\partial y} \frac{\partial \ln n^2}{\partial y} E_y \quad (2.12) \]

\[ \nabla^2 E_y + n^2 k^2 E_y = -\frac{\partial}{\partial y} - \frac{\partial \ln n^2}{\partial x} E_x - \frac{\partial}{\partial y} \frac{\partial \ln n^2}{\partial y} E_y \quad (2.13) \]

The slowly varying envelope approximation (SVEA) utilizes the assumption that the variation of the envelope of a travelling wave is spatially and temporally slower than its period or wavelength. The SVEA can only be used for signals that have a narrow band output to satisfy this condition, such as laser sources. The SVEA, shown in Eq. (2.14) can be applied to Eq. (2.12)
and (2.13) in conjunction with substituting $E_t = E_t e^{-i n_0 k z}$ in order to determine the paraxial full-vectorial beam propagation method equation, presented in Eq. (2.15) [11].

$$\frac{\partial^2 E_t}{\partial z^2} \ll 2 n_0 k \frac{\partial E_t}{\partial z}$$

(2.14)

$$\frac{\partial}{\partial z} E_x = -i \frac{P_{xx}}{2 n_0 k} \frac{P_{xy}}{P_{yy}} E_x$$

$$\frac{\partial}{\partial z} E_y = -i \frac{P_{yy}}{2 n_0 k} \frac{P_{xy}}{P_{yy}} E_y$$

(2.15)

In which,

$$P_{xx} E_x = \frac{\partial}{\partial x} \frac{1}{n^2} \frac{\partial}{\partial x} n^2 E_x + \frac{\partial^2 E_x}{\partial y^2} + n^2 - n_0^2 k^2 E_x$$

(2.16)

$$P_{yy} E_y = \frac{\partial^2 E_y}{\partial x^2} + \frac{\partial}{\partial y} \frac{1}{n^2} \frac{\partial}{\partial y} n^2 E_y + \frac{\partial^2 E_x}{\partial y^2} + n^2 - n_0^2 k^2 E_y$$

(2.17)

$$P_{xy} E_y = \frac{\partial}{\partial x} \frac{1}{n^2} \frac{\partial}{\partial y} n^2 E_y$$

(2.18)

$$P_{yx} E_x = \frac{\partial}{\partial y} \frac{1}{n^2} \frac{\partial}{\partial x} n^2 E_x$$

(2.19)

The BPM equation can then be rearranged to isolate the cross coupling terms, C and D, presented in Eq. (2.20), where $C = -i P_{xy}/2 n_0 k$ and $D = -i P_{yx}/2 n_0 k$ [11].

$$\frac{\partial}{\partial z} E_x = A_x + A_y \quad C \quad E_x$$

$$\frac{\partial}{\partial z} E_y = D \quad B_x + B_y \quad E_y$$

(2.20)

Where,
\begin{align*}
A_x E_x &= \frac{-i}{2n_0 k} \frac{\partial}{\partial x} \left( \frac{1}{n^2} \frac{\partial}{\partial x} E_x \right) + \frac{1}{2} n^2 - n_0^2 \ k^2 E_x \\
A_y E_x &= \frac{-i}{2n_0 k} \frac{\partial^2 E_x}{\partial y^2} + \frac{1}{2} n^2 - n_0^2 \ k^2 E_x \\
B_x E_y &= \frac{-i}{2n_0 k} \frac{\partial^2 E_y}{\partial x^2} + \frac{1}{2} n^2 - n_0^2 \ k^2 E_y \\
B_y E_y &= \frac{-i}{2n_0 k} \frac{\partial}{\partial y} \left( \frac{1}{n^2} \frac{\partial}{\partial y} E_y \right) + \frac{1}{2} n^2 - n_0^2 \ k^2 E_y
\end{align*}

These equations are used as the foundation of the Rsoft BeamProp software explained in section 3.1

2.2 Ray Tracing

Ray tracing is a technique that is used to determine the path a wave takes through an optical system consisting of various refractive media, media with different absorption characteristics and crossing different reflective surfaces. These characteristics can alter, bend, or change the direction of an incoming ray which complicates analysis. Ray tracing provides a solution by propagating a number of idealized narrow beams through the system and analyzing the interactions at each surface. Initially, ray tracing was performed by hand and required trigonometric and logarithmic tables to trace through the system [12]. However, it is now possible to have optical design software on a computer send hundreds or even thousands of rays at slightly different angles. The cross-sectional distribution of the rays can then be calculated at various distances. The theory that light waves can be modeled using rays remains valid so long
as the wavelength of light is much smaller than the object through which the light propagates.

One limitation of ray tracing is that it is not able to take into account the phenomenon of diffraction or interference since these rely upon the phase of the wave, which requires wave theory.

For homogeneous, isotropic media, such as silica glass in fiber, the rays travel straight until a surface is encountered. Each ray that is traced has its own position, polarization, and direction. At a surface, it is possible for the light to refract or reflect depending on the surface properties of the light and the media. After the rays have been traced from the source and through the system, it is possible to create a summation of the distribution of the density and direction of the rays in and those that exit the system. These results can then be used to predict a range of optical phenomenon. Of particular interest to fiber optics include optimal injection geometries, transmission losses, and modal distribution at critical areas.

The position and direction of a ray are its most fundamental properties in determining its propagation. It is possible to define the position using the vector, \( r = \{x, y, z\} \), and its direction using the vector, \( k = \{l, m, n\} \), whose values are the direction cosines of the unit vector along the ray path. The position of the ray at each surface can be calculated from its previous position and direction using Eq. (2.25), where \( t \) is the propagation distance. This can be applied throughout the entire system by calculating the new ray coordinates and direction cosines after every surface to determine the final image location.

\[
r' = r + tk
\]  

(2.25)
A light ray striking an intersection between two different isotropic media will refract according to Snell’s law, given in Eq. (2.26), where $n$ is the index of refraction of the respective media, and $\theta$ is the intersection angle measured from the normal to the boundary, as shown in Fig. 7.

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]  \hspace{1cm} (2.26)

Figure 7 - Refraction of light between two media where $n_2 > n_1$.

Snell’s law can be rewritten in vector form for ray tracing applications, as shown in Eq. (2.27), where $N$ is the vector normal to the point of intersection and $k$ is the ray direction cosine vector. Tracing reflection rays can be accomplished using this same equation by setting $n_2$ equal to negative $n_1$, as shown in Eq. (2.28) [13].

\[ n_1 \ N \times k_1 = n_2 \ N \times k_2 \]  \hspace{1cm} (2.27)

\[ N \times k_1 = -N \times k_2 \]  \hspace{1cm} (2.28)
Ray tracing can also be used to take into account the amplitude and phase of the electric field propagation. The amplitude of the ray can be expressed in the complex form, $Ae^{-i\phi}$, where $\phi$ is the phase variant. It is then possible to calculate the intensity of the ray which is the square of the ray amplitude. The amplitude is reduced slightly due to Fresnel reflections at the boundaries and though bulk absorption of the medium. The phase change of the ray varies according to Eq. (2.29), and can be kept track of using ray tracing by using the optical path length of the ray, which for isotropic media is simply the index of refraction multiplied by the distance travelled.

$$\phi = 2\pi \frac{tn}{\lambda}$$  \hspace{1cm} (2.29)

Additionally, whenever the light is reflected from a medium of higher index of refraction it will experience a phase shift of $\pi$ or 180°. When the light reflects from a medium of smaller index, the phase remains unchanged. These phase changes can become important for ray tracing in situations where interference occurs such as in thin films or in the design of anti-reflective coatings.

### 2.3 Optical Fiber Basics

An optical fiber is a flexible cylinder made out of silica or other types of glass that has a diameter that is on the order of the size of a human hair. It can function as a waveguide to transmit light between the two ends of the fiber [14]. Light is transmitted inside the core of the fiber with an index of refraction, $n_1$, which is surrounded by the cladding that has an index of refraction, $n_2$, that is less than the core. A hard coating and a buffer are sometimes used to encapsulate the fibers to protect it from mechanical perturbations, which could cause scattering.
losses. A cross section of the large core fiber used to determine losses around bends is shown in Fig. 8.

![Large core fiber cross section](image)

**Figure 8 - Dimensions of large core optical fiber marketed by 3M Specialty Optical Fibers [15].**

Light is transmitted with very little loss in optical fibers through the process of total internal reflection, as shown in Fig. 9. It was shown using Snell’s law in Fig. 7 that if light intersects a medium with a lower refractive index that the light will bend away from the normal. However, there exists an angle known as the critical angle, $\theta_c$, at which the light transmitted will be refracted at $90^\circ$, along the boundary between the medium. This critical angle can be calculated by setting the transmitted angle to $90^\circ$ in Eq. (2.26), and is presented in Eq. (2.30). Incident rays that strike the surface beneath the critical angle will split, with some reflecting off the surface and the rest passing through it. A ray striking the interface at an angle greater than the critical angle will reflect the entire incident light, which is called total internal reflection. It is important to note that this phenomenon only occurs when light is travelling from a medium with a higher refractive index to one with a lower one. This is the reason why the refractive index of the cladding of a fiber is slightly lower than that of the core.
Figure 9- Ray striking an interface to cause refraction, critical angle, and total internal reflection.

\[ \theta_c = \arcsin \frac{n_2}{n_1} \]  

(2.30)

An optical fiber with a core that is larger than 10 microns in diameter is called multi-mode fiber since there are multiple unique paths or modes that are lossless and can exist simultaneously within the core. The propagation of light within a multi-mode fiber is shown in Fig. 10, with each ray representing a separate mode. The amount of light that can be injected into the fiber is dependent on the numerical aperture, which can be calculated using Eq. (2.31), where \( \theta_{max} \) is the acceptance angle of the fiber. Light that enters the fiber at angles greater than the acceptance angle will refract into the cladding and be lost.
Figure 10- Rays propagating through total internal reflection within the acceptance angle of a multi-mode fiber.

\[ N.A. = n \sin \theta_{\text{max}} = \frac{n_{\text{core}}^2 - n_{\text{clad}}^2}{n_{\text{core}} - n_{\text{clad}}} \]  

(2.31)

The refractive index boundary between the core and cladding follows a step-index profile where the change in index changes abruptly. As light travels through the fiber, rays that enter close to the axis will travel faster due to a shorter optical path length than ones that enter off axis. This introduces modal dispersion such that there will be a difference between the times when different rays reach the end of the fiber. Graded-index fiber has a parabolic index change profile that is designed to minimize modal dispersion. However, since the fiber lengths used in the present work are at most only several meters, modal dispersion is negligible and step-index fibers are suitable.

The core of an optical fiber behaves as a circular dielectric waveguide that allows a set of certain electromagnetic waves to propagate within. Those fields are the modes and are governed by the cross sectional area of the core, the refractive index profile, and the frequency of the light. The
normalized frequency of the light can be calculated using Eq. (2.32), where \( a \) is the radius of the fiber core and \( \lambda \) is the wavelength of the light in vacuum. This can be used to calculate the mode volume, \( M \), which defines the number of modes that a multi-mode step-index fiber is capable of supporting, shown in Eq. (2.33). Large-core, step-index fiber used to transmit high energy in our experiments can propagate more than twenty-two thousand unique modes.

\[
V = \frac{2\pi a}{\lambda} \frac{n_{\text{core}}^2 - n_{\text{clad}}^2}{\lambda} \quad (2.32)
\]

\[
M = \frac{4V^2}{\pi^2} \quad (2.33)
\]

Large core multimode fiber follows electromagnetic wave propagation defined through Maxwell’s equations which can be transformed into the vector Helmholtz wave equations.

Consider a refractive profile of step-index fiber given in Eq. (2.34), where \( a \) is the radius of the core.

\[
n(r) = \begin{cases} 
n_{\text{core}}, & r < a \\
n_{\text{clad}}, & r \geq a 
\end{cases} \quad (2.34)
\]

Since the refractive index is independent of the propagation axis, \( z \), the field solutions to the wave equations can be rewritten in the polar coordinate form presented in Eq. (2.35) and (2.36), with \( r \) being the radius and \( \phi \) the azimuthal angle.

\[
E(r, \phi, z) = E_0(r, \phi)e^{-i\beta z} \quad (2.35)
\]

\[
H(r, \phi, z) = H_0(r, \phi)e^{-i\beta z} \quad (2.36)
\]
Here, $\beta$, is the propagation constant and is confined by the index of the core and cladding as well as the free space propagation constant, where $k_0 = \frac{2\pi}{\lambda}$ in order for the mode to propagate within the core.

$$n_{cladding}k_0 < \beta < n_{core}k_0 \quad (2.37)$$

It is possible to rearrange the $z$ component of the electric field using cylindrical coordinates for both inside and outside the core in Eq. (2.38). From there the solution for $E_z$ and $H_z$ can be solved in terms of the Bessel function, shown in Eq. (2.39) and (2.40), where $q$ is the integer azimuthal mode number, $\alpha$ is the constant phase shift, and $J_q$ and $H_q$ are the ordinary and modified Bessel functions of the first kind [16].

$$\nabla_z^2 E_{z\text{-core}} + n_{core}^2 k_0^2 - \beta^2 E_{z\text{-core}} = 0 \quad r \leq a \quad (2.38)$$
$$\nabla_z^2 E_{z\text{-clad}} + n_{clad}^2 k_0^2 - \beta^2 E_{z\text{-clad}} = 0 \quad r > a$$

$$E_z = A J_q \frac{ur}{a} \sin q\phi + \alpha e^{-i\beta z} \quad r \leq a \quad (2.39)$$
$$E_z = C K_q \frac{\omega r}{a} \sin q\phi + \alpha e^{-i\beta z} \quad r > a$$

$$H_z = B J_q \frac{ur}{a} \cos q\phi + \alpha e^{-i\beta z} \quad r \leq a \quad (2.40)$$
$$H_z = D K_q \frac{\omega r}{a} \cos q\phi + \alpha e^{-i\beta z} \quad r > a$$

Where the normalized transverse propagation constant is given by $u = a n_{core}^2 k_0^2 - \beta^2 \; 1/2$ and the normalized transverse attenuation constant is defined as $\omega = a \beta^2 - n_{core}^2 k_0^2 \; 1/2$. In a similar manner, the transverse field components can be resolved in Eq. (2.41)-(2.44), where $\sigma$ is the radian frequency, $\mu$ is the permeability tensor, and $\epsilon_0$ is the free space permittivity [17].
The modes of Eq. (2.39) – (2.44) can be analyzed by setting \( q = A = C = 0 \) such that the \( z \) and \( r \) components of the electric field and the \( \phi \) component of the magnetic field drops out, leaving only the nonzero transverse electric components of \( H_z, H_r, \text{and} \ E_\phi \), known as the \( TE_{0m} \) modes.

Alternatively, when \( q = B = D = 0 \) only the nonzero transverse magnetic components of
$E_z$, $E_r$, and $H_\phi$ remain, which are known as the $TM_{0m}$ modes. Lastly, the scenario whenever $q \neq 0$ corresponds to skew rays that follow a spiral path through the fiber and are represented through hybrid modes defined as either $EH_{qm}$ or $HE_{qm}$ modes.

The weak guiding approximation makes the assumption that $n_{\text{core}} \approx n_{\text{clad}}$, allowing the normalized index difference to be expressed in Eq. (2.45). This can be used with the boundary conditions to derive the modes eigenvalue equation shown in Eq. (2.46), where $l$ must be an integer [18]. Since the difference in refractive index between core and cladding is negligible, almost all of the $TM$, $TE$, and hybrid modes are degenerate. Therefore, it is acceptable to use a single notation of $LP_{lm}$ (linearly polarized) modes, where $l$ and $m$ are the number of radial and azimuthal zeros of a particular mode. The intensity distribution for various LP modes is presented in Fig. 11.

$$\Delta \approx \frac{n_{\text{core}} - n_{\text{clad}}}{n_{\text{core}}}$$    \hspace{2cm} (2.45)

$$u \frac{I_{l-1}}{J_l} u = -\omega \frac{K_{l-1}}{K_l} \frac{\omega}{\omega}, \quad l = q + 1 \quad TE_{0m}, TM_{0m}$$

$$q - 1 \quad EH_{qm}, HE_{qm}$$    \hspace{2cm} (2.46)
Figure 11- List of the intensity distribution for several LP modes produced with RP Fiber Power [19].
3. FIBER OPTIC MODELING SOFTWARE

3.1 RSofT BeamProp

RSofT is a suite of application modules that performs different types of optical simulations using a computer-aided design (CAD) software package. The module of interest is RSofT’s BeamProp software which specializes in designing and simulating fiber-optic waveguides using the beam propagation method. The software is able to use the finite difference solution of the Helmholtz equation shown in Eq. (3.1) to simulate the propagation of light in optical waveguides that have refractive indexes that are slowly varying, where \( k(x, y, z) = \frac{2\pi}{\lambda_0} n(x, y, z) \). The wavefunction, \( \psi \), can be defined in terms of the amplitude and phase of the wave using Eq. (3.2), where \( A \) is the amplitude and \( k \) is a constant used to describe the average phase change of the wavefunction along the z-direction.

\[
\nabla^2 + k^2 \psi = \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} + k^2 \psi = 0 \tag{3.1}
\]

\[
\psi(x, y, z) = A(x, y, z)e^{ikz} \tag{3.2}
\]

Substituting Eq. (3.2) into Eq.(3.1) results in Eq.(3.3). It is then possible to apply the second derivative of the wavefunction with regards to the z-direction to obtain Eq. (3.4). The expanded version of the Helmholtz equation is presented in Eq. (3.5) [20].

\[
e^{ikz} \frac{\partial^2 A}{\partial x^2} + e^{ikz} \frac{\partial^2 A}{\partial y^2} + e^{ikz} \frac{\partial^2 A}{\partial z^2} + k^2 A e^{ikz} = 0 \tag{3.3}
\]

\[
\frac{\partial^2 \psi}{\partial z^2} = e^{ikz} \left( 2ik \frac{\partial A}{\partial z} + \frac{\partial^2 A}{\partial z^2} - k^2 A \right) \tag{3.4}
\]
Whenever a light wave propagates further than a wavelength, the necessary iterations required to accurately solve the time harmonic solution becomes computationally unfeasible. To get around this, the slowly varying envelope approximation (SVEA), shown in Eq. (3.6) is utilized with the assumption that the envelope of a forward-travelling wave pulse varies slowly in time and space compared to the wavelength of light. The SVEA can be utilized in the expanded Helmholtz equation, Eq. (3.5), to solve for the fundamental equation used to solve BeamProp presented in Eq. (3.7) [21].

\[ e^{ikz} \left( \frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} + 2ik \frac{\partial^2 A}{\partial z^2} + 2ik \frac{\partial A}{\partial z} - k^2 A + k^2 A \right) = 0 \] (3.5)

This fundamental equation is an approximation so long as the electromagnetic field is very close to the z-axis. The solutions to the field structure in the x and y-direction are calculated initially and then found using discrete methods in subsequent calculations. For situations where the width of the waveguide is much larger than the wavelength, the wide angle BPM can be applied. This approximation can be derived by replacing the derivative with respect to z, \( \frac{\partial^2}{\partial z^2} \), with D, as shown in Eq. (3.8), where the operator constant P is given by Eq. (3.9).

\[ \frac{\partial^2 A}{\partial z^2} \ll 2ik \frac{\partial A}{\partial z} \] (3.6)

\[ \frac{\partial A}{\partial z} = \frac{i}{2k} \left( \frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} + A \right) k^2 - k^2 \] (3.7)

\[ D^2 + D \cdot 2ik + Pk^2 = 0 \] (3.8)

\[ P = \frac{1}{k^2} \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + k^2 - k^2 \right) \] (3.9)

The quadratic equation can be used to solve for D as follows.
The 1\textsuperscript{st} order Maclaurin series (Taylor series expansion about 0) can be applied to Eq. (3.11) to approximate \( \frac{1 + P}{1 + P} \), which results in the original fundamental BPM equation found in Eq. (3.7). It is possible to expand this series beyond the 1\textsuperscript{st} order to obtain even more accurate results [22]. A more accurate approximation is the Padé approximation, which is defined by a ratio of two power series, denoted by a numerator and denominator indices. For example, the Maclaurin series described would be denoted by the Padé order (1, 0) [23]. Rsoft allows the use of the following Padé orders depending on the required accuracy: (1, 0), (1, 1), (2, 2), (3, 3), or (4, 4). As the orders increase the paraxiality requirement is loosened, while also increasing the computational time [24].

Rsoft’s BeamProp relies on taking the first order derivative of the wavefunction along the direction of propagation (the z-axis) based on the launch conditions given. The solution to this equation is then used as the initial value problems for the next iteration after a certain distance along the z-axis. One of the key parameters of this model is the step size at which each computation is repeated. Early results indicate that when the z grid size is on the order of the wavelength of light of the laser, 1 micron, the solutions converge to provide the necessary accuracy. Since this model relies on integrating along the z-axis, direct simulation with curved waveguides breaks down whenever the radius of curvature of a bend is much greater than the width of the optical waveguide. In order to create a model incorporating these bends it was necessary to simulate a bend by using a conformal index mapping technique to transform the
geometry of a curved fiber into that of a straight segment. This technique allows the index of refraction to vary in order to account for the different optical path lengths light would experience in a bend. This perturbation in the index is given in Eq. (3.12), where $n$ is the static index of refraction of the core of the fiber, $n'$ is the refractive index representing the bent fiber, and $R$ is the radius of curvature of the bend.

$$n' = n \cdot \left(1 + \frac{\chi}{R}\right)$$  

(3.12)

A model was created of a fiber optic cable using the simulation parameters found in Table 1. A Gaussian laser beam with a 1064 nm wavelength was chosen as the injection source and the beam was set to come to a point and then expand approximately 1.5 mm from the front face of the fiber. This was designed so that the laser was intentionally under-filling the 0.22 NA fiber and that the $\frac{1}{e^2}$ beam width at the entrance was about 290 $\mu$m, or an 80% fill factor. This geometry had previously been determined by Setchell as being optimal for high energy fiber injection in order to minimize the chance of breakdown occurring on the front face [3].

| Table 1 – RSoft fiber specifications based on large core InnovaQartz fiber. |
|-----------------|----------------|
| Core Diameter   | 365 $\mu$m    |
| Cladding Diameter | 400 $\mu$m    |
| Core Index (at 1064 nm) | 1.4498      |
| Cladding Index ( at 1064 nm) | 1.4330      |
| Free-space Wavelength | 1064 nm      |

A simulation was designed to study mode mixing and compute the transmission loss through an optical fiber around bends of various radii. The laser beam was injected into a 5 cm long straight
section followed by a 90° bend of length equal to $\frac{2\pi R}{4}$. A second straight section of 5 cm in length was placed after the bend in order to examine the transformation of the Gaussian beam as it excites the fiber optic modes. A CAD representation of the layout used for single bend radius simulations is shown in Fig. 12.

![Bend Radius](image)

Figure 12- Layout of fiber cable wrapped around a mandrel to form a 90° bend.

Contour maps of the laser intensity in the fiber are plotted using the width (x-axis) and length (z-axis) was generated using BeamProp, shown on the left side of Fig. 13 and 14. These maps show how the Gaussian beam reflects through the bend causing it to more evenly distribute the intensity between the modes. Of particular interest are areas along the inner side of the bend in which the whispering gallery modes cause all of the light to group together on one side. For especially sharp bends such as that shown in Fig. 14, it can be seen how energy is coupled from the guided modes to radiation modes that are no longer confined to the core and result in transmission loss. If the energy density of the radiation modes becomes large enough, catastrophic damage can occur resulting in broken fibers. The normalized power transmitted was
monitored as function of propagation distance and is shown to the right of the contour map in each figure.

Figure 13- RSoft BeamProp intensity contour map of the core and cladding of the fiber though a 10 mm bend radius resulting in 96.5% transmission. From 0 to 5x10⁴ μm (5.0 cm) the fiber is straight showing the propagation of a Gaussian profile. The fiber bends begins at 5.0 cm and ends at about 7.5x10⁴ μm (7.5 cm) in which the whispering gallery mode can be seen along the right side of the profile and areas on the left side of the fiber can be seen where there is no light. After the bend the fiber is straight for 5.0 cm showing the mode mixing that occurs.
Figure 14- RSoft BeamProp intensity contour map of the core and cladding of the fiber though a 2.5 mm bend radius resulting in 24.9% transmission. From 0 to $5 \times 10^4 \, \mu m$ (5.0 cm) the fiber is straight showing the propagation of a Gaussian profile. The fiber bends begins at 5.0 cm and ends at about $6.0 \times 10^4 \, \mu m$ (6.0 cm) in which almost all of the light leaks out and escapes the cladding. In an actual experiment, this would indicate catastrophic damage occurring since the energy density of the light will have exceeded the bulk damage threshold of the silica glass.
BeamProp was used to run simulations of fiber transmission for bend radii between 2.0 and 11.5 mm as shown in Table 2. The total length of the fiber was 10 cm plus the length of the bend located at the end of the first 5 cm. These results were plotted in Fig. 15 with a loss in power transmission occurring for bend radii shorter than 7.5 cm.

<table>
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<th>Bend Radius (mm)</th>
<th>Power Transmission (%)</th>
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</tr>
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</tbody>
</table>
Figure 15- Transmission of the considered fiber (365 µm core, 400 µm cladding) versus radius of 90° bend, indicating drop in transmission for bend radii less than 7.5 mm.

The transmission of light through ‘S-bends’ in fiber in which two 90° bends occur within close proximity of each other was of particular interest due to previous data indicating unexpected failures at the outer edge of the 2nd bend. It was discovered using BeamProp that the distance between the end of one bend and the beginning of the 2nd bend can be optimized for optical transmission. A BPM model of the layout shown in Fig. 16 was designed using the same fiber characteristics and injection geometries described for the previous 90° bend tests. Radii of 6.0, 7.5, and 9.0 mm were chosen for the bends since these dimensions were on the edge of optimal performance for the previous tests. The distance between the bends was varied between 0.0 and 40.0 mm with. Intensity contour maps were generated for each set of parameters and the transmission was once again monitored, with two examples shown in Fig. 17 and 18. It can be seen in the intensity profiles that the light groups together along the outermost surface of the core.
of the fiber and forms a whispering gallery mode within the fiber. Once again, close examination shows that there exist certain sections around the innermost bends that contain no light.

Figure 16- Fiber layout for S-bend trial showing two 90° bends separated by a gap of varying length.
Figure 17- RSoft BeamProp intensity profile of fiber with a 7.5 mm ‘s-bend’ and no gap between bends resulting in a minimum transmission of 59.8%. A 5 cm straight section is in front of and behind the bends.
Figure 18- RSoft BeamProp intensity profile of fiber with a 7.5 mm ‘s-bend’ with a 2.0 mm gap between bends resulting in optimal mode-matching and a maximum transmission of 82.9%. A 5 cm straight section is in front of and behind the bends.

The transmission data for the 6.0, 7.5, and 9.0 mm radius of curvature s-bends was compiled and presented in Table 3 and plotted in Fig. 19. A distinct peak in output power was observed for all trials centered on a gap between bends of 2.0 mm. As the light exits a bend the light in the
whispering gallery modes in the first bend shifts to the opposite side of the core of the fiber which allows it to optimally enter the second bend. That is, the light enters the second bend already on the outer wall of that bend where it should be to be a whispering gallery mode in the second bend. Conversely, without this gap present, the light enters the second bend at too sharp on an angle, which causes the guided modes to escape the core and results in losses.

Table 3 – Transmission data for S-bends with a gap between the bends.

<table>
<thead>
<tr>
<th>Bend Spacing (mm)</th>
<th>6.0 mm bend</th>
<th>7.5 mm bend</th>
<th>9.0 mm bend</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Transmission (%)</td>
<td>Total Transmission (%)</td>
<td>Total Transmission (%)</td>
</tr>
<tr>
<td>0.1</td>
<td>36.6</td>
<td>59.8</td>
<td>71.7</td>
</tr>
<tr>
<td>0.5</td>
<td>39.2</td>
<td>59.5</td>
<td>74.7</td>
</tr>
<tr>
<td>1.0</td>
<td>45.3</td>
<td>65.0</td>
<td>82.5</td>
</tr>
<tr>
<td>1.5</td>
<td>56.6</td>
<td>77.0</td>
<td>90.7</td>
</tr>
<tr>
<td>2.0</td>
<td>62.8</td>
<td>82.9</td>
<td>93.7</td>
</tr>
<tr>
<td>2.5</td>
<td>60.0</td>
<td>80.7</td>
<td>93.3</td>
</tr>
<tr>
<td>2.8</td>
<td>55.8</td>
<td>78.8</td>
<td>90.3</td>
</tr>
<tr>
<td>3.0</td>
<td>53.5</td>
<td>75.1</td>
<td>88.5</td>
</tr>
<tr>
<td>4.0</td>
<td>45.4</td>
<td>65.0</td>
<td>76.9</td>
</tr>
<tr>
<td>5.0</td>
<td>50.2</td>
<td>69.5</td>
<td>83.2</td>
</tr>
<tr>
<td>6.0</td>
<td>53.9</td>
<td>70.6</td>
<td>86.2</td>
</tr>
<tr>
<td>7.0</td>
<td>49.4</td>
<td>68.4</td>
<td>84.4</td>
</tr>
<tr>
<td>8.0</td>
<td>49.4</td>
<td>70.3</td>
<td>84.8</td>
</tr>
<tr>
<td>9.0</td>
<td>51.3</td>
<td>73.2</td>
<td>84.7</td>
</tr>
<tr>
<td>10.0</td>
<td>48.6</td>
<td>70.6</td>
<td>84.0</td>
</tr>
<tr>
<td>15.0</td>
<td>52.9</td>
<td>74.7</td>
<td>85.1</td>
</tr>
<tr>
<td>20.0</td>
<td>51.4</td>
<td>71.7</td>
<td>85.1</td>
</tr>
<tr>
<td>25.0</td>
<td>50.4</td>
<td>71.7</td>
<td>85.1</td>
</tr>
<tr>
<td>30.0</td>
<td>47.8</td>
<td>71.0</td>
<td>85.1</td>
</tr>
<tr>
<td>35.0</td>
<td>47.8</td>
<td>71.0</td>
<td>85.1</td>
</tr>
<tr>
<td>40.0</td>
<td>46.8</td>
<td>69.9</td>
<td>85.1</td>
</tr>
</tbody>
</table>
A final experiment was setup to examine the effect of whispering gallery modes on power transmission through bends by modeling a 180° bend made up of two 90° bends separated by varying gaps. A bend radius of 7.5 mm was chosen so that there would be contrast between maximum and minimum transmission and the gap between the bends was varied in similar increments to the s-bend trials. The s-bend data indicates that optimal transmission occurs when the light is confined to the whispering gallery modes or if necessary, when the bends are mode-matched. Therefore, it would follow that a gap would only introduce additional losses into the system. The data collected is presented in Table 4 and then plotted in Fig. 20.

Figure 19- Power transmission through an S-bend with a gap between bends, indicating a peak in transmission centered at 2.0 mm.
Table 4 – Transmission data for a 180° bend with 7.5 mm bend radius and a gap between bends.

<table>
<thead>
<tr>
<th>Bend Spacing (mm)</th>
<th>Total Transmission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>95.8</td>
</tr>
<tr>
<td>0.5</td>
<td>89.8</td>
</tr>
<tr>
<td>0.75</td>
<td>82.5</td>
</tr>
<tr>
<td>1</td>
<td>74.7</td>
</tr>
<tr>
<td>1.25</td>
<td>68.8</td>
</tr>
<tr>
<td>1.5</td>
<td>63.5</td>
</tr>
<tr>
<td>2</td>
<td>59.1</td>
</tr>
<tr>
<td>2.5</td>
<td>58.2</td>
</tr>
<tr>
<td>2.75</td>
<td>63.1</td>
</tr>
<tr>
<td>3</td>
<td>67.3</td>
</tr>
<tr>
<td>4</td>
<td>74.7</td>
</tr>
<tr>
<td>5</td>
<td>71.5</td>
</tr>
<tr>
<td>6</td>
<td>67.7</td>
</tr>
<tr>
<td>7</td>
<td>73.4</td>
</tr>
<tr>
<td>8</td>
<td>71.1</td>
</tr>
<tr>
<td>9</td>
<td>67.7</td>
</tr>
<tr>
<td>10</td>
<td>70.3</td>
</tr>
</tbody>
</table>

Figure 20- Transmission performance through a 180° bend indicating maximum output when there is no gap and a minimum output when the gap is centered at 2.0 mm.
The transmission data for the 180° bend is approximately opposite of the results for the s-bend, which is expected since it was previously shown that it takes 2.0 mm for the light to propagate from one side to the other after a bend. The BeamProp results when there is no gap are presented in Fig. 21. Of particular interest is that the transmission is within 1% of that for the single 90° bend. This suggests that once the light enters the whispering gallery modes of the fiber it will no longer experience significant losses as it makes its way around the 180° bend. To confirm this theory, a simulation was run with 10 360° loops which resulted in a transmission of 95.1%, approximately the same transmission of a single 90° bend.
Figure 21- RSoft BeamProp intensity profile of fiber with a 7.5 mm 180° bend with no gap between bends resulting in a maximum transmission of 95.8%. A 5 cm straight section is in front of and behind the bends.

3.2 Zemax Non-Sequential Ray Tracing

Zemax is an optical design software package that is capable of performing non-sequential ray tracing for use in optimizing optical systems and providing stray light analysis. Since there are a
large number of modes capable of propagating within the fiber, it is possible to treat the simulation as a light-pipe. A light source can be defined and geometric image analysis can then be used to generate the total irradiance at any surface. A model of the 90° fiber bend was created using the same fiber dimensions and injection geometry used for the Rsoft BeamProp trials, shown in Fig. 22. It is important to note that there are sections along the inner curve of the fiber that don’t have any light passing through them due to the formation of whispering gallery modes. These light rays can travel almost perfectly guided around a concave surface through total internal reflection.

Figure 22- Zemax schematic of 90° bend with a 9 mm bend radius demonstrating whispering gallery modes. The light rays computed by Zemax are shown in blue.

A ray trace with 1000 rays was chosen to obtain a statistically significant sample size with the energy associated with each ray initially being equal. Detectors to measure the intensity
distribution of the cross-sectional area of the core of the fiber were placed at 0°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, and 90° around the bend and the recordings are presented in Fig. 23. It can be see that at 30° most of the light is along the outer edge of the fiber and that at 45° the light is completely in the whispering gallery modes. As the rays exit the bend they shift from the outer side of the core to the opposite side until it eventually leads to a more uniform distribution within the core.

Figure 23- Zemax cross-sectional intensity distributions for a 9 mm bend radius at angles of a) 0° b) 30° c) 35° d) 40° e) 45° f) 50° g) 55° h) 60° and i) 90°
The propagation of the light was examined after the bend by placing additional detectors immediately after the bend, 3.77 mm after the bend, and 7.14 mm from the end of the bend, shown in Fig. 24. This indicates that it takes approximately 3.77 mm for the grouped rays to travel from one side of the fiber to the opposite side. This distance is important since it shows how far apart s-bends should be to achieve mode-matching into the second bend such that optimal transmission occurs. Another point of interest is that after 7 mm the modes in the fiber become more evenly distributed, which suggests that there is little difference in transmission between gaps of 7 mm and any larger distances. The intensity shift and the uniform distribution distances agree well with the RSoft BeamProp results presented in Fig. 18.

Figure 24- Zemax cross-sectional intensity distributions after a 9 mm bend at distances of a) 0.0 mm b) 3.77 mm c) 7.14 mm
4. BEND RESULTS AND CONCLUSIONS

4.1 Experiment Introduction

Laser damage experiments were performed on large diameter core fibers using a 10 Hz, Nd:YAG, Q-switched laser. The fibers were routed through various bend radii consisting of single 90° bends and “S-bends” in which two 90° bends occur in close proximity to each other. The transmission through the fiber was monitored as a function of bend radius and catastrophic damage was noted when the transmission would drop significantly. A technique for maximizing the transmission through bends that was discovered through mathematical modeling was verified in the lab. Lastly, a bend radius that would survive for a 30-year lifetime was calculated using COMSOL Multiphysics modeling by extrapolating the static stress placed on fiber through fiber bend tests. These results agreed well with previous work performed by Setchell and Klingsporn and are in alignment with models produced using Rsoft’s BeamProp and Zemax non-sequential ray tracing.

A sketch of the experimental setup used to perform laser damage testing on the optical fibers is shown in Fig. 25. The laser used was a Quanta-Ray Q-switched, Nd:YAG laser capable of delivering up to 2000 mJ in an 8-12 ns pulse width at 1064 nm. The laser operated at a repetition rate of 10 Hz which allowed a series of pulses to be transmitted through the fiber while monitoring the transmitted power until it dropped to 0, indicating the occurrence of laser damage. Since the energy of the laser is much higher than is needed for our requirements, the surface of an uncoated wedge was used to reflect ~4% of the beam and a combination of polarizers was used to control the laser output. The spot size of the beam was approximately 8
mm, making it slightly larger than the 5 mm size that would be ideal for optical injection. Using an aperture to reduce the beam size would considerably vignette the power and would run the risk of adding diffraction effects that could cause early damage. Therefore, a system of two lenses was chosen to couple the light into the fiber such than the size of the beam on the entrance face was about 300 µm or ~80% of the diameter of the core. A beam splitter was inserted between the polarizers and the injection lenses so that a 5 mW, 632.8 nm HeNe laser could provide a reference beam for laser alignment and to track the power loss through the polarizers.

Figure 25- Sketch of experimental setup used for fiber damage testing, created using ORA LightTools.

The fiber optic cables were drawn from a Heraeus fused silica core step index multimode Fluosil preform which provides a fluorine-doped silica cladding for better transmission in the near-infrared. Fibers were produced by InnovaQuartz and were specified with the diameter of the core
as 365 +/- 14 µm with a cladding diameter of 400 +/- 8 µm. Their high concentricity and low core-to-clad ratio provided for optimal connector alignment and increases that chance of injecting successfully into the core of the fiber. The fibers also had a 425 +/- 10 µm diameter TEQS hard-polymer coating that increased the strength of the fiber and reduced static fatigue from stripping and breaks. Lastly, the fiber had a 730 +/- 30 µm diameter buffer which provides additional mechanical strength for bending the fiber. At 1064 nm the index of refraction is 1.4498 for the silica core and 1.433 for the cladding, yielding a numerical aperture of 0.22. The recommended operating temperature of the fiber is between -65 and + 125 ° C. A list of the full fiber specifications is given in Appendix A. The fiber was cleaved and polished by Coastal Connections according to the procedure shown in Appendix B, which was established by Akinci at Los Alamos National Laboratory (LANL)[25].

The transmission through the fiber was measured using the setup shown in Fig. 26. A fiber microscope was used to examine the front face of the fiber before each trial to confirm that the polish was smooth. Two AR coated lenses with focal length of 1013 and 754 mm were placed 25.4 mm apart in order to focus the beam from a spot size of 7 mm to 102 µm over a focal length of 43.1 cm. The fiber tip was placed at a distance of 43.8 cm from the lens so that the beam expands as it enters the fiber. A green He-Ne laser was used to assist in fiber optic injection alignment with the use of a high reflectivity mirror at 532 nm. A rotatable half-wave plate was used to adjust the power into the fiber and reference energy measurements were taken by with an Ophir 30A thermopile detector A more detailed picture of the injection optics along with the incident energy control scheme is given in Fig. 27.
Figure 26- Overview of experimental setup used to inject high-energy laser light into fiber optic cables.

Figure 27- Injection optics and incident energy and incident energy control scheme used to measure and control how much energy strikes the fiber.
The temporal pulse width of the Spectra Physics Quanta Ray laser was measured using a Thorlabs fast silicon photodiode (SV2-FC) and captured with a Tektronix digital storage scope (TDS 694C). The impulse response time of the photodiode was verified to be approximately 500 ps using a picosecond laser operating at 1064 nm on the 1 GHz/5GS/s storage scope. The full-width half-max (FWHM) measurement of 12.3 ns is shown in Fig. 28, which agrees well with the specification of 8-12 ns.

Figure 28- FWHM measurement of 12.3 ns on the pulse width of the Spectra Physics Quanta Ray laser at 1064 nm.
4.2 Whispering Gallery Modes

The formation of whispering gallery modes (WGM) was predicted by Zemax and RSoft to occur when light propagating through a fiber experiences a bend. Quarter sized mandrels with a bend radius of 9 mm were constructed to experimentally observe WGM’s through a 90°. The mandrels were made of Delrin so that the fibers could slide easily through the bend. A HeNe laser was used to inject light into the fiber and an imaging microscope was used to record images of the output of the fiber. The microscope was positioned on a translation stage and the fiber was pushed through the bend in small increments in order to image the pattern of light exiting the fiber face. The fiber was defined to exactly at the 90° bend when the face of the fiber and the Delrin face were simultaneously in focus. For subsequent measurements, the microscope was translated so that the front face was in focus and the micrometer position was recorded. This was performed up a distance of 7.14 mm since it was predicted and observed that the modal distribution is random after this point.

The intensity distribution shift of the light from the outermost side of the fiber to the inner side is shown in Fig. 29. The two white spots in the images are reflections of the room lights off the end face of the fiber. The light can be seen completely in the WGM in image ‘a’ with slightly less than half the fiber containing almost no light. Between image ‘a - 0.00 mm’ and image ‘g - 3.77 mm’, the light shifts from the right (outer side of the bend) to the left (inner side of the bed). The light completely fills the entire fiber by image ‘i – 7.14 mm’. This agrees well with the Zemax cross-sectional intensity distributions shown in Fig. 24. Additionally, this agrees with the optimal gap between s-bends presented with RSoft in Fig. 19 because the transmission of light through a bend is optimized when the light enters the bend already positioned to be a WGM.
Figure 29- Microscope images of the exit surface of a 365 µm core diameter fiber going around a 9 mm bend radius at varying distances from the bend. The spatial distribution shift of the light can be seen as the light propagates from the outer edge of the fiber in image ‘a’ to the inner edge by image ‘g’.
4.3 Laser Damage Study

The transmission through a 90° bend in the fiber was measured as a function of bend radius for radii between 6.5 and 12.5 mm. The input energy of the laser was held constant at a lower energy of 2.3 mJ per pulse and a repetition rate of 10 Hz in order to isolate any effects due to damage on the front face or non-linear effects. The results through 1000 shots is shown in Fig. 30, which indicates that at low energies the bend radius has little effect on the transmission for bends with radius of curvature larger than 6.5 mm. The variation between trials can easily be explained with slight misalignments between setups; however it is assuring that all are within a few percent of each other.

![Graph showing transmission through a 90° bend over 1000 pulses using a constant input energy of 2.3 mJ at a repetition rate of 10 Hz.]

Figure 30- Transmission through a 90° bend over 1000 pulses using a constant input energy of 2.3 mJ at a repetition rate of 10 Hz.
Laser damage testing was initially performed by increasing the amount of energy incident upon the front face of the fiber until ablation was observed at the fiber tip. At energies higher than 15 mJ damage was observed in the microscope directly in the center of the core of the fiber with no damage occurring outside of the fiber. After damage occurred the transmitted energy would drop to around 5 mJ per pulse. Laser damage tests were performed on bends by securely fastening the fibers to mandrels using strips of Delrin and Teflon. The fiber was routed around a 6.35 mm bend and the incident energy was set to 6 mJ. The transmitted energy was recorded to be 4.5 mJ or 80%, which agrees to within 5% of the transmission predicted with the BeamProp software. Catastrophic failure was observed after approximately 530 shots, as shown in Fig. 31. A visible red HeNe laser was injected into the fiber so show the change before and after the damage occurred. Additionally, the HeNe was used to examine the specular reflection off of the fiber tip before and after damage occurred around the bend. Both images were identical which indicated that the surface had not been ablated.
Figure 31- a) Scattered visible light leaking through the buffer accounting for the 20% losses through the 6.35 mm bend. b) Visible light escaping the fiber after damage occurred. c) Magnified image of catastrophic damage.

4.4 Observation of Stimulated Brillouin Scattering

During the course of performing laser damage experiments it was observed that the transmission would decrease whenever the energy per pulse was increased above a certain level. At low energy levels, such as those shown in Fig. 30, the transmission would remain constant. However, for higher input energies the transmission would decrease linearly. It was noted that the transmission drop was temporary and when the input energy was dropped back to lower levels that the transmission percentage would recover. This threshold level occurred at approximately 3.5 mJ with the 12.3 ns pulse at 1064 nm. This phenomenon appeared to be independent of the
radius of curvature of the bend in the fiber, as indicated by the data plotted in Fig. 32. The drop in energy was initially believed to be caused by a form of scattering since no catastrophic damage was visible in the bend region, however none was detected.

Figure 32- Transmission measurements through a 365 μm diameter core fiber consisting of a 15 cm straight section followed by a 90° bend of varying curvature. A decrease in transmission can be seen for incident energies higher than 3.5 mJ for the 12.3 ns, 1064 nm pulse.

Based on the suggestion of Prof. B. Zeldovich, the light exiting the entrance face of the fiber was monitored to determine if stimulated Brillouin scattering (SBS) was causing the light to reflect back towards the direction of the laser. SBS can occur in a medium such as an optical fiber when the laser is intense enough to cause the variation in the electric field to produce acoustic vibrations. These vibrations cause the incoming light to scatter in the opposite direction and optical phase conjugation to take place. Fresnel reflections off of the fiber face were recorded at low energy levels by using a beamsplitter to separate the reflected light. If SBS were occurring, it
would be expected that at higher energy levels the reflected light would be significantly increased per pulse. SBS was observed for input energy levels larger than 3.5 mJ, shown in Fig. 33. This is problematic since in addition to depleting the forward transmission, damage can occur when the energy density exceeds the bulk damage threshold of the silica glass.

Figure 33- Fast detector amplitude oscilloscope measurements. Below 3.5 mJ consist solely on Fresnel reflections and above 3.5 mJ includes Fresnel and SBS recordings.

4.5 Mechanical Failure Study

Static mechanical bend tests were performed on the optical fiber by wrapping it around several mandrels of varying radii of curvature and measuring the time it took for each bend to break. The fibers were kept in the bend by using a translation stage to keep them under tension. A frequency doubled CW Nd:YAG laser operating at 532 nm was injected into the fiber and an imaging microscope was used to detect any mechanical failures. Initially bends of radius between 7.5 mm and 12.5 mm were used, however after two weeks of monitoring no failures were detected. At
this point mandrels of 3.0, 4.0, and 6.5 mm were constructed and once again the fibers were pulled taught with a micrometer drive. Each fiber that was wrapped around the 3 mm bend failed instantly. On average, the fibers wrapped on the 4.0 mm bends lasted for 30 hours and 20 minutes. Lastly, the fibers bent around the 6.5 mm bends did not fail after several days. The natural logarithm of the failure time of the fiber is inversely proportional to the natural logarithm of the stress induced by the bend, as shown by Tandon, Buchheit, and Berry [26]. The results for the fiber bend test were plotted against the stress on the fiber, shown in Fig. 34. These results served as data points for modeling the stress in the bent fibers using COMSOL Multiphysics.

![Figure 34](image)

Figure 34- The natural log of the stress of a bent fiber is inversely proportional to the natural log of the bend radius.
Using the manufacturer specifications given in Appendix A, a model of the fiber was created in COMSOL. Information was widely available about the mechanical properties of the core and cladding, however obtaining data on the TEQS hard polymer coating and the TEFZEL buffer proved more challenging. The TEQS layer was ignored and the TEFZEL was extended to encompass the area this would have been in since the TEQS layer was only 12.5 μm thick. A Poisson’s Ratio of 0.17 was assumed since this is a common value for similar materials and it varies little. Young’s Modulus was determined using the bend measurements described above. It was discovered when performing the bend tests that the mechanical information provided by Thorlabs was overestimating the value for Young’s Modulus. The coefficient for the cladding was set to 53 GPa based on results found in literature surveys resulting in a calculated Young’s Modulus for the TEFZEL of between 120 and 250 MPa as opposed to 72.5 GPa as reported by the manufacturer. This is in agreement with the 177.8 that was determined graphically using the Dupont TEFZEL Properties Handbook chart that compares stress to strain. This allowed the maximal stress on the axis tangent to the bend to be calculated for a simulated 180° bend in a fiber, shown in Fig. 35.
Figure 35- Stress placed on a 4 mm radius bent fiber along the x-axis.

The COMSOL simulations along with the linear regression of the logarithm of the stress to the logarithm of the radius that was shown in Fig. 36 was used to derive an equation for the expected time until failure for this fiber, given in Eq. 4.1.

$$ t = (5.7717 \cdot 10) r^{40.3229} \quad (4.1) $$

It was then possible to extrapolate that the minimum allowable bend radius the 365 μm diameter core fiber with a TEFZEL protective jacket could survive for 30 years is 5.0 mm based on the graph in Fig. 36. This value is in agreement with previous fiber tests performed by Klingsporn at Honeywell FM&T [4].
Figure 36- Expected failure time for 365 μm diameter core fiber with a TEFZEL jacket based on the radius of curvature of the bend in the fiber. A black line shows the 30-year lifetime.
5. CONCLUSIONS

5.1 Conclusions

Over the course of this project, simulations showing the interaction and transmission of light through bends in fiber optic cables were developed using two independent software packages, RSoft’s BeamProp and Zemax. Experiments in the lab validated much of what was predicted by the models and also served as a reminder that even the best laid out theoretical estimates are unable to incorporate all of the tribulations and complexities that exist in the real world. Static fiber bend tests were able to calculate the stresses as a function of bend radius, which in turn allowed a recommended minimum bend radius to be determined.

Utilizing two methods of simulation provided separate methods of evaluating unique aspects of the fiber. The beam propagation method used by RSoft was able to visually display the light modes as they are transmitted through the fiber, which proved especially useful when examining the changes through tight bends. Additionally, by examining the transmission data provided by the BPM package we were able to learn what design features could be used to maximize the light output through the fiber. Alternatively, it was with the ray tracing software Zemax that the formation of whispering gallery modes within the bends of the fiber was first realized. The cross-sectional intensity distributions generated with Zemax along with the modal distributions of BPM independently led us to the conclusion that it is possible to maximize the transmission through S-bends. This was achieved by separating the bends by a 3 mm spacing which resulted in a maximum transmission that was in some cases 100% more than with no spacing. This occurs because it allows the grouped light to transverse laterally along the fiber such that it enters the second bend already positioned to form a whispering gallery mode. A provisional application for
a patent has been filed recognizing this simple but effective method for designing fiber routing geometries.

The experimental results were able to confirm much of what was initially demonstrated with the modeling programs. The formation of whispering gallery modes and the grouping of the modes for several mm after the bend was proven with microscope images of laser light within the core of the fiber. Also, catastrophic damages were observed for bend radius less than 6.35 mm which is in agreement with models indicating significant transmission losses below 6.5 mm. The static testing showed that the fiber being tested could survive a 30-year lifetime at a bend radius of 5.0 mm, which does not take into account sending high energy laser light through it. This is reassuring since it agrees well with the 6.0 mm recommended by Klingsporn over a decade ago. As a result, it is this team’s recommendation that the absolute minimum bend radius for the tested 365 µm diameter core fiber be is 7.5 mm in order to survive both the static 30-year lifetime as well as the transmission of high energy laser light. That being said, a bend radius of 10.0 – 15.0 mm would be able to provide the necessary margin to insure the desired reliability.

One area that remains uncertain and requires additional study is the observation of stimulated Brillouin scattering for laser energies greater than 3.5 mJ. It was unexpected since it was believed that the large area of the core would prevent the energy density of the laser from producing acoustic vibrations. Especially troubling, was the observance in setups where the fiber was not routed around any bends. It is outside the scope of this study, but it is believed that examining the relationship between SBS and the linewidth of the laser being used may indicate a
method of increasing the input energy by broadening the laser source to a multimode source with a spacing of more than 50 GHz.

Overall, there is increased confidence in utilizing systems that require high energy (GW/cm²) optical fiber routings as a result of the optical modeling simulations developed, whispering gallery mode observations, laser damage study, and fiber static fatigue tests performed. The following recommendations are suggested for future systems:

- The minimum bend radius for transmitting high energy laser light through large core optical fibers is 7.5 mm.
- Optical fibers can be routed through loops of similar radius as 90° bends without additional losses due to the formation of whispering gallery modes.
- Optimal transmission occurs through an S-bend when a 3 mm gap is added between the bends. This gap allows the light to enter into the 2nd bend so that it is mode-matched to enter the whispering gallery modes.
**TEQS PowerFlex™ Fiber Specifications**

**Stability** of silica cladding allows higher power-handling capability and laser misalignment.

**Low-index**, fluorine-doped silica cladding design provides superior UV and near-IR transmission compared to polymer-clad fibers and doped core, silica/silica fibers with low auto-fluorescence.

**High concentricity** and low core-to-clad ratio for excellent connector alignment and small overall fiber size for close pack bundle terminations.

**TEQS hard-polymer** coating yields increased fiber strength and reduced static fatigue, protects the fiber during stripping to prevent fiber damage and breaks and produces a dual waveguide effect for evanescence and core overfill containment, resulting in unparalleled power throughput under extreme bending conditions.

**Covalent bonding** between silica and IQinc TEQS prevents fiber pistoning for more stable terminations.
<table>
<thead>
<tr>
<th>Core Diameter (m)</th>
<th>150 ± 6</th>
<th>200 ± 8</th>
<th>273 ± 10</th>
<th>345 ± 14</th>
<th>500 ± 19</th>
<th>940 ± 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica Cladding Diameter (m)</td>
<td>180 ± 4</td>
<td>240 ± 5</td>
<td>300 ± 6</td>
<td>400 ± 6</td>
<td>600 ± 10</td>
<td>1000 ± 15</td>
</tr>
<tr>
<td>2nd Cladding (TEGS) Diameter (m)</td>
<td>200 ± 6</td>
<td>280 ± 6</td>
<td>325 ± 10</td>
<td>425 ± 10</td>
<td>620 ± 10</td>
<td>1050 ± 15</td>
</tr>
<tr>
<td>Buffer Diameter (m)</td>
<td>300 ± 25</td>
<td>400 ± 30</td>
<td>420 ± 30</td>
<td>720 ± 30</td>
<td>1040 ± 20</td>
<td>1400 ± 50</td>
</tr>
<tr>
<td>Full Acceptance Cone Angle</td>
<td>25° primary</td>
<td>45° secondary*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Power Standard Input</td>
<td>0.3 kW</td>
<td>0.56 MW</td>
<td>0.4 kW</td>
<td>1.0 MW</td>
<td>0.57 kW</td>
<td>1.85 MW</td>
</tr>
<tr>
<td>Operating Temperature (°C)</td>
<td>65 to 135</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Proof Test Level (psi)</td>
<td>150</td>
<td>130</td>
<td>130</td>
<td>125</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Minimum Bend Radius (m)</td>
<td>0.6</td>
<td>1.2</td>
<td>1.8</td>
<td>3.4</td>
<td>3.2</td>
<td>3.0</td>
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<tr>
<td>Recommended Bend Spacing*</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Standard Length (m)</td>
<td>1100, 2200</td>
<td>1100, 2200</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td><strong>NA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Low (OH)</strong></td>
<td>0.22 ± 0.02</td>
<td>0.29 ± 0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>High (OH)</strong></td>
<td>0.26 ± 0.02</td>
<td>0.35 ± 0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Broad Spectrum</strong></td>
<td>0.29 ± 0.02</td>
<td>0.39 ± 0.03</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Maximum Attenuation @ 850nm</td>
<td>12 dB/km</td>
<td>12 dB/km</td>
<td>12 dB/km</td>
<td>12 dB/km</td>
<td>12 dB/km</td>
<td>12 dB/km</td>
</tr>
</tbody>
</table>

1. Standard buffer coating is blue colored Teflon® R10 – nylon and Hytrel® may be available upon request.
2. Based on 3 kW/m² for 150um OD, 1/4 in. payloads and input spot size equal to 50% of the core diameter for mechanically polished terminations.
3. Based on 3 kW/m² for 100um OD, 1/4 in. payloads and input spot size equal to 50% of the core diameter, standard polish.
4. Recomended as a standard option. All other parts are available upon request and are subject to availability of the chosen fiber type.
5. Standard bend radii are equal to 1.25 times the bend radius of the fiber, 100% of proof test level, based upon statistical analysis of fiber failures.
6. Standard bend radii are equal to 2.5 times the bend radius of the fiber, 100% of proof test level, based upon statistical analysis of fiber failures.

* High (OH) 150um core is FO1500CR based upon 150um cores to FO1500CR.
* High (OH) 200um core is FO2000CR based upon 200um cores to FO2000CR.
APPENDIX B: LANL POLISHING PROCEDURE
REFERENCES


15) http://www.fiberguide.com/product/optical-fibers/


