DESIGN, FABRICATION, AND DEMONSTRATION OF SQUARE HOLEY DIELECTRIC THZ WAVEGUIDES

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DESIGN, FABRICATION, AND DEMONSTRATION OF SQUARE HOLEY DIELECTRIC THZ WAVEGUIDES

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DESIGN, FABRICATION, AND DEMONSTRATION OF SQUARE HOLEY DIELECTRIC THZ WAVEGUIDES

A Dissertation Presented to the Graduate Faculty of the
Lyle School of Engineering
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in
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Doctor of Philosophy
with a
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by
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A variety of novel dielectric THz waveguides were demonstrated to increase a channel capacity in a chip-to-chip communication system. Square holey cladding dielectric THz waveguides were designed, fabricated, and characterized. The single-material holey cladding waveguide is low loss and easy to fabricate compared to doped core fibers. The square geometry supports two states of polarization with minimum cross-talk for polarization division multiplexing applications. Simulations show the waveguide supports two states of polarization across the frequency range of 180 GHz to 360 GHz. In addition, simulations show good mode isolation and low bending losses. Holey cladding square waveguide was fabricated using a custom-built draw tower to preserve the square geometry. TOPAS was chosen from several studied dielectrics for its low material loss and fabrication capabilities. Fabricated waveguides were shown to support the mode despite manufacturing defects. Fiber loss measurements showed a 24 dB/m loss that approach the accepted material loss of TOPAS (22 dB/m). THz vortex waveguides were demonstrated for space division multiplexing applications for the first time. The holey cladding TOPAS-based vortex waveguide was designed to preserve orbital angular momentum for $\ell=1$ and 2 at 280 GHz. The output power of the waveguide for different $\ell$ and core sizes were studied. The waveguide was fabricated with the custom-built draw tower. Transmission of a first order OAM beam at 280 GHz was experimentally demonstrated. The first order, $\ell=1$, Laguerre-Gaussian beam was generated with a custom-made spiral phase plate. Inspired by the vortex waveguide design, several low-loss
square holey core/cladding waveguides were designed and simulated for polarization division multiplexing. The waveguides combine the benefits of low loss and broadband transmission, while supporting two states of polarization. The boundary conditions created by the holey cladding confine the beam to the holey core for a low loss transmission. Three square holey core/cladding designs were proposed. These designs include a single-hole core, a nine-hole core, and a core comprised of four square capillary tubes. The square capillary tubes exhibits 7 dB/m, which is significantly lower than the material loss of TOPAS (22 dB/m).
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This is dedicated to my parents, Alireza Aflakian and Mahin Farshad.
Chapter 1
INTRODUCTION

The generation of pulsed terahertz (0.1 THz to 10 THz) electromagnetic waves began in the 1970s and early 1980s when optical pulses from mode-locked lasers became short enough (picosecond pulses) to yield the necessary THz bandwidth [1], [2]. In very early experiments the ultra-short optical pulse was rectified by a photoconductor (PC) antenna comprised of two metal electrodes on a semiconductor substrate separated by a gap [3], [4]. Since then, THz electromagnetic waves have been generated through a variety of techniques, including optical rectification, quantum cascade lasers (QCLs), and air plasma THz generation [5], [6], [7]. In optical rectification, a THz beam is generated from optical beating in a nonlinear crystal using a picosecond pulsed laser. QCLs are a recent source of THz radiation enabled by nanotechnology advances first demonstrated at Bell Laboratories in 1994. THz waves are radiated by QCLs due to a subband transition of a quantum well staircase potential. In air plasma THz generation the fundamental mode of an optical pulse and its second order are focused into ambient air to generate THz radiation. Solid state electronic devices have also been used to generate THz radiation by mixing two signals having slightly different frequencies that yield the generated wave frequency [8]. THz wave generation was also recently demonstrated in a lens-less silicon CMOS architecture [9].

A variety of THz wave detectors have been developed. An unbiased photoconductor antenna and optical rectification have been used to detect THz waves [10]. The electro optic responses of birefringent crystals have also been used [11]. CMOS Schottky diode detectors [12] and diode-connected NMOS transistors [13] are examples of THz detectors used for imaging.

The use of THz radiation in experimental systems or commercial applications invariably requires additional components to focus, guide or otherwise manipulate the signal. Since
THz waves fall between the infrared (IR) and microwave spectral regions, most passive THz components have been inspired by either optical or microwave/RF components. For instance, parabolic mirrors and dielectric lenses similar to optical components, are routinely used in THz applications. Since the wavelength of THz radiation is much larger than optical wavelengths, fabrication precision is not typically a challenge.

Examples of THz components evolved from the microwave region are rectangular and circular cross section metallic waveguides. Circular cross section waveguides [14] are made of metallic shells and exhibit ohmic loss due only to the metallic surface. Metallic parallel plate waveguides [15] exhibit ohmic loss due to the plates and divergence loss at the open sides of the waveguide. Bare metal wires [16] are made of thin wires that define boundary conditions for propagation. Propagating waves are loosely confined to the wire and mostly propagate in the air surrounding the single wire. This results in lower ohmic loss but with poor mode confinement, a shortcoming that may be improved by using two metal wires [17], [18]. Fabrication challenges including manufacturing precision and ohmic loss impairments are also encountered when scaling from the microwave region to the THz region. In this work, dielectric THz waveguides have emerged as an alternative to ohmic losses that are principally due to metal surface roughness.

The geometry and fabrication processes of THz dielectric waveguides have been adopted from optical and IR fibers. THz dielectric waveguides are divided into hollow, solid, and porous core designs. Hollow core waveguides offer low loss since waves propagate in the hollow core but lack bending flexibility since they are a few millimeters thick [19] [20]. Capillary tubes have been used for low loss THz transmission based on total internal reflection or anti-resonant reflection depending on the operating frequency [21]. There is a large variety of solid core waveguides, though they suffer from material loss. To lower the material loss, a low loss material may be chosen and the core size may be reduced. However, core reduction also reduces mode confinement. In light of these considerations, solid core holey waveguides are an attractive solution for lower material loss, good mode confinement, and support for broadband transmission.
An application of waveguides is the interconnection between electronic chips. Metallic/electric interconnects are traditionally used for chip-to-chip interconnects. High frequency data communication is approaching a bottleneck due to ohmic losses inherent in metallic interconnects [20]. Optical interconnects could provide a solution to lower the loss. Unfortunately, moving toward optical interconnects requires efficient electro-optical conversion at transmitter and receiver ends that has yet to be practically developed. Dielectric THz waveguides have been developed for chip-to-chip communications using the native radiation of electronics. THz waveguides are to fill in the gap between the electric and optical interconnects while exploiting the advantages of both. THz interconnects have lower loss compared to electric interconnects, and there is no need for electro-optical conversion.

In this dissertation, multiple dielectric THz waveguides are demonstrated for chip-to-chip communication using native THz radiation. The presented THz waveguides have two novel characteristics, holey cladding and square cross section.

Since all dielectric waveguides presented for chip-to-chip communications have evolved from RF and microwave waveguides, these waveguides usually have no cladding. For example, Thienen, et al., [22] presented a circular plastic waveguide with no cladding as a CMOS communication link. Reynaert, et al., [23] presented a copper-coated rectangular polypropylene fiber as a link for CMOS communication systems. A cladding provides beam isolation to avoid bending loss or losses due to external perturbations, while preserving the waveguide flexibility. A beam travels inside such a waveguide due to total internal reflection created by the refractive index mismatch of the core and cladding. To create a cladding, the core refractive index is typically increased by doping the fiber core. This increases absorption and scattering losses due to the added ions. In this work, holes in the cladding are used to reduce the cladding index. This method combines the benefits of low loss with ease of fabrication compared to doped fibers. A graded index cladding also decreases the modal dispersion in a multimode fiber.

The square cross section of the waveguide allows for polarization division multiplexing (PDM) with minimal cross-talk compared to conventional circular fibers. A square geometry
supports equally both vertical and horizontal states of polarization. The square fiber also
maintains states of polarization. Many circular waveguides with complicated geometries
have been proposed as polarization maintaining fibers. Atakaramians, et al., [24] proposed a
set of highly birefringent THz circular fibers having rectangular shaped holes with different
sizes to create a birefringent fiber. Hasan, et al., [25] proposed a porous-core spiral THz
waveguide. Its spiral symmetry consists of nine circular rings with ten spiral arms. Each
arm consists of nine air holes of various diameters. Here, the presented square fiber is
polarization maintaining with a simple geometry that allows for increased fabrication yield.

In Chapter two, the design, fabrication and characterization of a square dielectric THz
waveguide for PDM applications is presented. First, Finite-difference time-domain (FDTD)
simulations were used to design and simulate fiber loss, bending loss, and effective refrac-
tive index as a function of frequency. The average refractive index of the waveguide was
calculated as a function of the distance from the center and the fundamental mode of the
waveguide was calculated analytically. The mode confinement as a function of core size was
studied for different frequencies. The square fiber was then fabricated using a custom-built
draw station to preserve the square geometry of the waveguide. The THz waveguide was
later characterized using a vector network analyzer (VNA) connected to a pair of frequency
extenders operating in the sub-THz region. The mode profile of the waveguide was mapped
while the receiver module, covered by a pinhole, stepped across the cross section of the waveg-
uide output. The waveguide loss was measured using the VNA. An asymmetric coupling
component connected to the frequency extenders was used to increase the coupling efficiency
at both ends of the fiber for loss measurements. A taper with an aperture size close to the
waveguide core was used to couple the beam into the waveguide efficiently. A horn with an
aperture size bigger than the waveguide size was used to couple the beam out of the fiber
efficiently. Three waveguides with different lengths were tested for loss measurement. The
longer the waveguide, the higher the measurement accuracy. The measured fiber loss was in
agreement with the simulated fiber loss.
In Chapter three, a THz square vortex fiber is presented for space division multiplexing (SDM) applications. A vortex fiber is designed to transmit orbital angular momentum (OAM) endowed beams. Multiple OAM beams may travel in the same channel with minimum cross talk since they are orthogonal to each other. The THz vortex waveguide was designed, fabricated, and experimentally tested for the first time. The square vortex THz waveguide was simulated by FDTD modeling and studied with the first two OAM orders at 280 GHz. Vortex fiber characteristics such as power loss and effective refractive index were simulated for different core sizes and the average refractive index of the vortex fiber was calculated as a function of the distance from the center. The fiber was then fabricated using the custom-built oven. Successful transmission of the first order OAM beam was experimentally demonstrated using an \( \ell = 1 \) OAM endowed beam generated by passing a plane wave generated by vector network analyzer through a fabricated stepped spiral phase palate. The OAM characteristic at the output of the vortex fiber was verified by a second, vertically inverted, discrete step spiral phase plate.

In Chapter four, several square holey core/cladding designs are presented for broadband and low loss transmissions. The goal was to reduce loss by forcing most of the beam to travel through a holey core. Here, the beam propagation mechanism is different from conventional solid core fibers. The holey cladding acts as a boundary condition to keep the beam confined to the core. The geometries of the presented waveguides show an average loss reduction factor of 1.3 to 3, depending on the design. The presented waveguides operate in the frequency range of 180 GHz to 360 GHz while supporting both vertical and horizontal states of polarization equally. The fabrication techniques are discussed in each case for the interested reader.

A summary and discussion of the results is provided in Chapter five.
2.1. Introduction

In this Chapter, the development of a square dielectric holey cladding THz waveguide is presented for application in polarization division multiplexing (PDM) method used to double the capacity.

A fiber consists of a core and cladding with the latter having a lower refractive index to trap a beam inside the core and protect the fiber against bending losses and losses due to external perturbations. Two common methods are used to create a fiber cladding. In one method, the fiber is doped to raise the core index. The other method is to create holes in the cladding to lower the cladding index. While doping material to create a core raises the loss tangent, holey cladding fibers offer a lower loss solution. Holey cladding fibers also benefit from ease of fabrication and lower fabrication costs in the same manner as photonic and hollow photonic crystal fibers do.

When multiplexing a channel capacity, low mode cross talk is crucial. Circular fibers suffer from crosstalk since they are not polarization maintaining in general. To create a polarization maintaining circular fiber, the symmetry must be broken using an asymmetric pattern [24], [25]. Unfortunately, once the fiber symmetry is broken, the fiber can not support x- and y- states of polarization with identical phase and group velocity [26], [27] so efficient polarization division multiplexing is impossible.

Unlike circular fibers, square fiber geometry supports x- and y- states of polarization and is polarization maintaining that provides less crosstalk. Thus, polarization multiplexing for a data communication application is more robustly implemented with square fiber geometries. In addition, square waveguides may offer the advantage of close-packing a ribbon of
waveguides.

A square holey cladding waveguide is used here for the first time as an interconnect for chip-to-chip communications. To this end, the presented design uses the lowest possible number of holes to provide higher fabrication yield. The square holey geometry described herein allows a broad band (180 GHz to 360 GHz) transmission.

A cyclic olefin copolymer (COC) commercially known as TOPAS was chosen from among a variety of dielectric materials for its low loss [20]. The presented square waveguide is smaller than cylindrical holey TOPAS [28] and Zeonex [29] waveguides.

In this Chapter, the design and simulation of square holey cladding TOPAS waveguides is presented. Different dielectric square waveguide characteristics such as operation frequency, losses, refractive indices, mode confinement and isolation were simulated and studied. Then, the fabrication process is presented. The fabrication process, including differences between the custom-built draw tower and conventional fiber drawing processes, were designed to facilitate the square waveguide geometry. Next, successfully fabricated fibers were characterized. The transmitted waveguide mode profile was measured using a vector network analyzer (VNA) by stepping a pinhole across the output facet of the waveguide. The waveguide loss was measured using a free space dielectric material characterization method. Here, a taper with an aperture comparable to the core size was used. The taper provides easy alignment and higher coupling efficiency. A horn antenna at the output was used to increase the coupling efficiency out of the fiber. The measured fiber loss was compared to the simulated data and the material loss of the dielectric (TOPAS).

The measured fiber loss (0.24 dB/cm) is comparable to other chip-to-chip dielectric interconnects. Yu, et al., [30] presented a micromachined silicon dielectric waveguide with a measured fiber loss of 14 dB/cm. A dielectric waveguide made of Rogers R3006 was used as a chip-to-chip interconnect with a measured fiber loss of 0.5 dB/cm [31]. A copper-polymer blend waveguide presented by Reynaert, et al., shows a low fiber loss of 0.025 dB/cm [23]. A silicon on glass THz waveguide was demonstrated with 0.57 dB/cm fiber loss [32].
2.2. Physical Characteristics of the Waveguide

A square waveguide was developed to link the transceivers of a 300 Gbps communication link as shown schematically in Figure 2.1. The square geometry of the waveguide was designed to support both vertical and horizontal states of polarization. The waveguide size was defined to accommodate the operation frequency of 180 GHz to 360 GHz. The holey cladding provides a low loss fiber that is straightforward to fabricate.

![Figure 2.1. A CMOS transceiver system for 300-Gbps communication over a dielectric waveguide](image)

A number of dielectric materials, commonly used for THz applications (Table 2.1) were studied. Polymethylmethacrylate (PMMA) and polycarbonate (PC) are the traditional materials used in optical fibers. Though these polymers have low material loss in the optical region (PC loss of 0.02 dB/cm [33] and PMMA loss of 0.01 dB/cm [34] at 500 THz), they suffer from high material loss in the THz region (about 8.7 dB/cm for PC and 8.6 dB/cm for PMMA at 300 GHz). Teflon and quartz have low loss in the frequency range of interest, but they require advanced manufacturing capabilities. Polypropylene material loss strongly depends on its polymer chain type (co-polymer polypropylene or homo-polymer polypropylene as shown in Table 2.1) and manufacturing conditions. A cyclic olefin copolymer (COC), known as TOPAS, was chosen for this project as it was consistently reported to exhibit low material loss [20], [28]. In addition, TOPAS showed high fabrication yield and is non-toxic as its main application is in food packaging, so there was no need for specialized fabrication facilities.
Table 2.1. Material loss for candidate materials for THz waveguides.

<table>
<thead>
<tr>
<th>Material</th>
<th>n</th>
<th>0.2 THz</th>
<th>0.3 THz</th>
<th>0.5 THz</th>
<th>1 THz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymethylmethacrylate (PMMA) [28]</td>
<td>1.5</td>
<td>4.3</td>
<td>8.6</td>
<td>25</td>
<td>87</td>
</tr>
<tr>
<td>Polycarbonate (PC) [35]</td>
<td>1.63</td>
<td>4.3</td>
<td>8.7</td>
<td>13</td>
<td>43</td>
</tr>
<tr>
<td>Polypropylene, Homo-Polymer (PP) [36]</td>
<td>1.53</td>
<td>0.26</td>
<td>0.35</td>
<td>0.39</td>
<td>1.43</td>
</tr>
<tr>
<td>Polyethylene (PE) [37]</td>
<td>1.51</td>
<td>0.22</td>
<td>0.30</td>
<td>0.65</td>
<td>1.74</td>
</tr>
<tr>
<td>TOPAS [28]</td>
<td>1.53</td>
<td>0.19</td>
<td>0.24</td>
<td>0.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Fused silica [38]</td>
<td>1.45</td>
<td>0.10</td>
<td>0.20</td>
<td>0.33</td>
<td>1.5</td>
</tr>
<tr>
<td>Polypropylene, Co-Polymer (PP) [36]</td>
<td>1.50</td>
<td>0.10</td>
<td>0.17</td>
<td>0.26</td>
<td>0.74</td>
</tr>
<tr>
<td>Teflon (PTFE) [20]</td>
<td>1.43</td>
<td>0.07</td>
<td>0.10</td>
<td>0.40</td>
<td>2.17</td>
</tr>
<tr>
<td>crystalline Quartz [38]</td>
<td>1.45</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
<td>0.35</td>
</tr>
</tbody>
</table>

2.3. Design and Simulation

Simulations of the square waveguide were done using the BeamProp package of the RSoft software [39]. The simulation process is detailed in Appendix A. The simulation begins by defining the physical characteristics of the waveguide such as its size, hole configuration, material refractive index, and material losses. To calculate the mode using the BeamProp mode computation, a given incident beam (e.g. Gaussian) that is z-invariant is launched into the structure. Note that the mode of a waveguide depends on the waveguide characteristics and is independent of the incident beam. Since the structure is uniform along the z-axis, the solution can be expressed in terms of the modes of the waveguide as a function of x and y and a propagation constant in the z direction. Considering the separation of variables, the incident field ($\phi_{in}(x)$) can be expanded in the guided and radiation modes of the structure,

$$\phi_m(x, z) = \sum_m c_m \phi_m(x) e^{i\beta_m z},$$

(2.1)

where $m$ is the mode number and $\beta$ is the propagation constant. The propagation distance, $z$, is replaced by $iz'$ so,
\[
\phi_{in}(x, z) = \sum_{m} c_m \phi_m(x) e^{\beta_m z'}. \tag{2.2}
\]

Each mode has a growth rate proportional to its real propagation constant. The fundamental mode of the waveguide has the highest growth rate and dominates all other modes after propagating a certain distance. After a certain propagation distance, \( z_c \), only the fundamental mode, \( \phi_0(x, z_c) \), remains. All higher order modes may be obtained by exploiting their orthogonality characteristics.

Using the RSoft mode computation package, several different hole configurations were simulated. The fundamental mode profile of the waveguide was simulated in steady state within the frequency range of 180 GHz to 360 GHz. The goal was to identify and optimize a design supporting the mode across this frequency range with a minimum number of holes. The requirement of fewer holes is to enable higher manufacturing yields. Fig. 2.2 shows examples of various simulated hole configurations.

Figure 2.2. Different hole sizes and geometries were studied. The accepted design must support the fundamental mode in the range of 180 GHz to 360 GHz, with the fewest number of holes for ease of fabrication.
Fig. 2.3 shows the accepted fiber design for a 2 mm × 2 mm TOPAS waveguide with eight 400 µm diameter holes and approximately 1 mm core size. The core size of the waveguide is on the order of the wavelength or smaller.

![Waveguide Design](image)

Figure 2.3. A 2 mm × 2 mm waveguide with eight holes (400 µm diameters) was chosen for fabrication. The waveguide core is comparable to the operating wavelength (0.83 µm to 1.7 µm).

2.3.1. Mode Profile

The steady state simulations of the electric field at the output of the fiber for vertical and horizontal states of polarization are shown in Fig. 2.4. Figs. 2.4(a) and 2.4(b) indicate good mode confinement at 360 GHz for x- and y- polarizations. Figures 2.4(c) and 2.4(d) show the simulation at 180 GHz for both polarizations.
Figure 2.4. The mode profile of the designed waveguide simulation. The electric field at the cross section of the waveguide at 360 GHz is shown for (a) $x$-polarized and (b) $y$-polarized modes. The electric field at the cross section of the waveguide at 180 GHz is shown for (c) $x$-polarized and (d) $y$-polarized modes. Simulations show the mode is well-confined at 360 GHz. However about 50% of the beam is in the cladding at 180 GHz. This is due to the wide operation bandwidth. While the beam is well confined at 360 GHz, some mode leakage is expected at lower frequencies.

2.3.2. Averaged Refractive Index as a Function of Distance from the Center

The refractive index of the waveguide is calculated as a function of square contours of half width $s[\mu m]$ as shown in the inset of Fig. 2.5. The core refractive index is considered to be 1.5258 [28] since the center is only TOPAS. The cladding refractive index is calculated
as a weighted average using [40]

\[ n = \sum (n_{air}f_{air} + n_{TOPAS}f_{TOPAS}) \]  

(2.3)

where \( n_{air} \) and \( n_{TOPAS} \) are the refractive indices of the materials and \( f_{air} \) and \( f_{TOPAS} \) are the linear fractions covered by each material. The refractive index of the holey waveguide is the weighted average of the core and cladding. The latter consists of air holes and TOPAS. The use of square contours allows comparison with the refractive index profiles of typical cylindrical waveguides. Figure 2.5 shows the averaged refractive index as a function of \( s \).

Figure 2.5. The averaged refractive index, \( n \), of the waveguide as a function of square contours is shown radiating outward from \( s=0 \) \( \mu \text{m} \) to \( s=1000 \) \( \mu \text{m} \). The refractive index from \( s=0 \) to \( s=500 \) \( \mu \text{m} \) is a constant value for TOPAS, 1.5258. At \( s=500 \) \( \mu \text{m} \) the refractive index begins to decrease due to the presence of the eight holes. At \( s=750 \) \( \mu \text{m} \) from the center of the waveguide the refractive index is minimum and returns to 1.5258, since at \( s=900 \) \( \mu \text{m} \) there are no air holes. (Inset) A schematic cross section of the waveguide showing a square contour \( s \) [\( \mu \text{m} \)]. The cladding holes were 400 \( \mu \text{m} \) in diameter and the overall dimension of the waveguide is 2 mm \( \times \) 2 mm.

As shown in Fig. 2.5, the refractive index in the holey cladding follows an approximately quadratic function. The fundamental mode of this waveguide was analytically calculated in
one dimension using the Helmholtz equation as follows.

For simplicity, only the portion of refractive index from $x=0$ to $x=750 \, \mu m$ was considered. The refractive index profile is

\[
 n = \begin{cases} 
 1.5258 & (0 \mu m < x < 500 \mu m) \\
 ax^2 + bx + c & (500 \mu m < x < 750 \mu m) 
\end{cases} 
\] (2.4)

where $a = 5.47 \times 10^{-6} \mu m^{-2}$, $b = -8.1 \times 10^{-3} \mu m^{-1}$, and $c = 4.18$ (by fitting the refractive index calculated and shown in Fig. 2.5).

Beginning with the Helmholtz equation in one dimension,

\[ \Delta^2 \psi(x) + [K^2(x) - \beta^2] \psi(x) = 0, \] (2.5)

where $K$ is the wave-number as a function of $x$, and $\beta$ is the propagation constant.

Considering the $y$-polarization ($H_y = E_x = E_z = 0$) the electric and magnetic fields are given by:

\[
 H_x = -\frac{\beta \psi(x)}{\omega \mu_0} \\
 E_y = \psi(x) \\
 H_z = -i \frac{d\psi(x)}{\omega \mu_0 dx} 
\] (2.6)

The solution to equation (2.5) in the range of $0 < x < 500 \, \mu m$ (for constant $k$) is well-known to be
\[
\psi_1(x) = A \cos(kx)
\]  \hspace{1cm} (2.7)

where

\[
k = \sqrt{k_0^2 n_{\text{TOPAS}}^2(x) - \beta^2}.
\]  \hspace{1cm} (2.8)

with \( k_0 = 2\pi/\lambda_0 \) and \( \lambda_0 = 1667 \, \mu\text{m} \).

However, the solution in the range of 500 \( \mu\text{m} \) to 750 \( \mu\text{m} \) is unknown. An arbitrary solution of \( \psi(x) = B \exp(-g(x)) \) is considered in the Helmholtz equation (2.5). Solving the Helmholtz equation results in

\[
\psi_2(x) = B \exp\left[-\int \kappa(x) dx\right]
\]  \hspace{1cm} (2.9)

where

\[
\kappa(x) = \sqrt{\beta^2 - k_0^2 n^2(x)}.
\]  \hspace{1cm} (2.10)

Boundary conditions are applied to find \( \beta \). The boundary conditions are the continuity of tangential \( H \) and \( E \) fields, or \( \psi(x) \) and \( d\psi(x)/dx \) at \( x = 500 \, \mu\text{m} \), as follows

\[
A \cos(kx) = B \exp\left[-\int \kappa(x) dx\right]
\]  \hspace{1cm} (2.11)

and

\[
-Ak \sin(kx) = -B\kappa(x) \exp\left[-\int \kappa(x) dx\right].
\]  \hspace{1cm} (2.12)

Dividing the boundary conditions, gives the transcendental equation
\[ -k \tan(kx) = -\kappa(x) \]  

(2.13)

where

\[ \kappa(x) = \sqrt{k_0^2 \left[ n_{TOPAS}^2 - n^2(x) \right] - k^2}. \]  

(2.14)

Equation (2.13) may be plotted to find \( k = 0.00096 \, \mu m \) and ultimately \( \beta = 0.0057 \, \mu m \) (using equation (2.8)) as shown in Fig. 2.6.

Figure 2.6. The transcendental equation (2.13) gives the value of \( k \) and ultimately \( \beta \).

Using these values,

\[ \psi_2(x) = B \exp \left[ -\int \sqrt{\beta^2 - k_0^2(ax^2 + bx + c)^2} \, dx \right]. \]  

(2.15)

The equation was simplified by a binomial expansion and only the first two terms were used. After integration, equation (2.15) becomes
\[
\psi_2(x) = B \exp \left[ - \left( x - \frac{k_0^2}{2\beta^2} t \right) \right]
\]

(2.16)

where

\[
t = 5.9842 \times 10^{-12} x^5 - 2.2154 \times 10^{-8} x^4 + 3.711 \times 10^{-5} x^3 - 0.033858 x^2 + 17.472 x
\]

(2.17)

Figure 2.7 shows the normalized, one-dimensional fundamental mode of the waveguide, \(\psi(x)\), and the average refractive index, \(n_{\text{Avg}}(x)\).

Figure 2.7. The averaged calculated refractive index of the waveguide (right vertical axis) and the analytic normalized fundamental mode of the waveguide (left vertical axis).

The comparison between the analytic mode and the horizontal cut of the RSoft calculated mode is shown in Fig. 2.8. The slight difference between the analytic and simulated results may be due to the errors in the average refractive index calculations and ignoring higher terms of the binomial expansion.
2.3.3. Effective Refractive Index vs Frequency

The effective refractive index, \( n \), of the square fiber was calculated with RSoft. The BeamProp simulation calculated the propagation constant as explained in section 2.3. The real part of the propagation constant is related to the real effective refractive index. Fig. 2.9 shows \( n \) for both states of polarization. The refractive indices are identical for vertical and horizontal states of polarization as expected from the symmetry of the square geometry. The effective refractive indices increase as the frequency increases since the majority of the beam is confined to the core with higher refractive index as shown in Fig. 2.5. At lower frequencies the refractive index decreases since a portion of the beam is traveling through the air holes that have lower refractive index as shown in Fig. 2.5.
Figure 2.9. Effective refractive index of the waveguide shown in Fig. 2.4 across the frequency range of interest for $x$- and $y$- polarizations. As the frequency decreases the effective refractive index decreases. This could be better understood by looking at Fig. 2.4(d) and Fig. 2.5. Fig. 2.4(d) shows that some portion of the beam is in the cladding, which has lower refractive index (compared to the core) as shown in Fig. 2.5.

2.3.4. Loss Measurement

To simulate waveguide loss from normalized output power, imaginary values of the TOPAS refractive index were calculated using reported bulk material loss [28]. This data was given to the program. Loss simulation steps are detailed in section A.1.4. To measure the fiber loss, the same algorithm explained in section 2.3 is used. This time the program looked at the imaginary portion of the propagation constant that is associated with fiber loss. Figure 2.10 shows the normalized power along a 10 cm length of a TOPAS waveguide with a 2 mm × 2 mm cross section and 8 holes along the length of the waveguide. The simulations are done at 200 GHz and 300 GHz.
Figure 2.10. Simulated output power normalized to input power of a 10 cm fiber for (a) 200 GHz and (b) 300 GHz. Simulation shows a fiber loss of 0.19 dB/cm at 200 GHz and 0.25 dB/cm at 300 GHz. The simulated waveguide loss is slightly higher than the TOPAS material loss (0.19 dB/cm and 0.23 dB/cm at 200 GHz and 300 GHz, respectively) due to the imposed waveguide boundary conditions.

As shown in the simulation, the fiber loss is slightly higher than the material loss. This is due to boundary conditions created by the waveguide, which leads to leakage before the mode settles.

2.3.5. Bending Loss Studies

Bending losses were simulated for four bending radii of infinity, 25 mm, 12 mm, and 10 mm across the frequency range of 180 GHz to 360 GHz. Fig. 2.11(a), (b), and (c) show bending loss simulations for a 10 mm bending radius at 180 GHz. Fig. 2.11(d) shows the output power along the length of the waveguide. As shown in Fig.2.11(c), the beam is leaking as it propagates in the curved section of the waveguide. This leakage results in a drop in the output power as shown in Fig. 2.11(d).
Figure 2.11. (a) Bending loss design and (b) simulation for a 10 mm radius of curvature at 180 GHz. (c) Monitored normalized power along the length of fiber. The power decreases after $z= 5000 \, \mu m$ due to bending loss leakage as shown in (b).
Figure 2.12 shows the power loss measured for four bending curvatures across the frequency range of 180 GHz to 360 GHz. The straight waveguide shows a higher loss at lower wavelengths, which is expected as discussed in section 2.3.3. Fig. 2.12 shows that the bending loss increases as the radius of curvature decreases. Importantly, the bending loss is larger at higher wavelengths. A bending loss comparison between the straight waveguide and a curved one, e.g. with a 10 mm radius of curvature, at different wavelengths shows the bending loss is higher as the wavelength increases. This is due to the fact that at smaller wavelengths the beam is well isolated and confined to the core and will not leak if the fiber is bent.

![Figure 2.12. Power loss for four bend curvatures of infinity (no bend), 25 mm, 12 mm, and 10 mm in the wavelength of 0.83 mm to 1.67 mm (360 GHz to 180 GHz).](image)

2.3.6. Single Mode Versus Better Isolation

Ideally a single mode waveguide is desired to avoid modal dispersion [41]. However, this is not possible due to the wide frequency bandwidth. The core size must be reduced to
achieve single mode. This decreases the mode confinement. This issue was addressed by looking at the mode confinement of three designs with different core sizes, as shown in Fig. 2.13.

Design (a) is the original design, a 2 mm × 2 mm waveguide with eight 400 µm diameter holes. Its design is discussed in section 2.3.1. This design is not single mode at any frequency across 180 GHz to 360 GHz. However, the mode is well-confined to the core in this design. As shown in Fig. 2.13 an average of about 91% of the beam in confined to the core.

Design (b) is a 1.6 mm × 1.6 mm waveguide with eight 360 µm diameter holes. This waveguide is single mode across the frequency range of 180 GHz to 190 GHz and 75% of the mode is confined to the core.

Design (c) is a 1.2 mm × 1.2 mm waveguide with eight 320 µm diameter holes forming the cladding to support a single mode across 180 GHz to 220 GHz. The average power confinement to the core for design (c) is only 45 %. Due to the wide operating frequency, beam isolation becomes an issue while trying to achieve a single mode waveguide. Lack of mode isolation introduces bending loss or loss due to external perturbations. Design (a) was chosen here since mode isolation was more important than single mode. In addition, this fiber doesn’t suffer from modal dispersion since it has graded index, as shown in Fig. 2.5.
Figure 2.13. Power core confinement of three different core sizes chosen for single mode studies at different frequencies. Design (a) a 2 mm × 2 mm waveguide with eight 400 µm diameter holes, shows an average of 91% core-confinement. Design (b) A 1.6 mm × 1.6 mm waveguide with eight 350 µm diameter holes. In this design an average of 71% of the beam is confined to the core. Design (c) a 1.2 mm × 1.2 mm with eight 300 µm diameter holes. Power in the core is an average of 45% of the total power.
2.4. Fabrication

A number of different processes are used to fabricate holey fibers, including tube stacking, micro-structured molding, and a drill-and-draw technique [42]. The most widely used method is tube stacking, in which capillary tubes are stacked and arranged to create a preform from which a fiber is drawn. Microstructure molding may be done by casting the desired material into a mold to create a preform. In this case, the drawn fibers are kept under solvent for days to etch the cast and yield structured holey fibers. In another microstructure molding technique, the preform is made by casting the desired material into a mold. The mold is then pulled out to make the holey preform structure from which fibers will be drawn. The drill and draw fabrication process consists of three steps: making preform, drilling holes into preform, and heated fiber drawing from preform. First, a preform is made by heated molding of the raw material. Then the holes are drilled into the preform. The preform shrinks into a fiber by applying controlled heat and pulling tension. The drill and draw technique was chosen for this work due to its ease of fabrication with a small number of required holes.

2.4.1. Making the Preform

To make preforms, a custom mold was designed and machined from stainless steel. The cross sectional dimensions of a typical preform is 35 mm × 35 mm as precisely determined by the mold and calculated based on empirical preform-to-fiber shrink ratio data. To ensure sufficient material for fiber drawing, a typical preform is approximately 9 cm tall.

The mold was cleaned and sprayed with boron nitride to prevent the material from sticking to the sidewalls. Molds were preheated using a hot plate at 157°C. The temperature was then increased to 210°C and 10 layers of 20 ml of TOPAS beads were sequentially added every 20 minutes. The preform was annealed for 40 minutes in a convection oven at 230°C. The hot plate temperature and melting time were controlled to give a uniform block of TOPAS.
Figure 2.14. (a) Raw TOPAS beads before melting and molding. (b) An aluminum assembled mold. (c) A uniform block of TOPAS preform.

Fig. 2.15 shows the preform molding steps. Each step was fine-tuned and optimized to create a uniform block of TOPAS to avoid formation of air bubbles and impurities. Existence of air bubbles and impurities interfere with the drawing process in addition to increasing scattering and absorption losses of the waveguide.
Figure 2.15. Preform fabrication steps. First, molds were preheated using a hot plate at 157°C for 90 minutes. 6 layers of 20 ml of TOPAS beads were sequentially added to the mold every 20 minutes. The temperature was then increased to 210°C and 4 layers of 20 ml of TOPAS beads were sequentially added every 20 minutes. The preform was annealed for 40 minutes in a convection oven at 230°C.

2.4.2. Hole Definition

Holes were drilled with 1μm precision through the TOPAS preform at their designed locations (10 mm pitch) using a mechanical drill press and drill bit size of 3/16”. The shrink factor of preform-to-fiber dimensions was experimentally determined. The shrink factor of the core, cladding, and holes were determined to be 15.8 ± 1, 17.5 ± 1, and 13.1 ± 1, respectively. Using shrink factor data, the 3/16” drill bit was used on the preform to achieve a 400 μm diameter hole size in the fiber. The hole-drilling process was done very slowly using water and in some cases WD-40 as lubricant to avoid drill bits from sticking in the preform and to ensure smooth holes in the drawn fiber.
Figure 2.16. The holes were drilled in their designed locations using a drill press. The drawing process was done very slowly with water and, in some cases WD-40 to achieve smooth holes.

2.4.3. Fiber Drawing

The last step is the heated fiber drawing. A custom drawing tower was built to preserve the square geometry of the fiber. The fibers were successfully drawn using the drawing station. In this section, first the drawing station apparatus is explained. Next, the fiber drawing process is detailed.

2.4.3.1. Drawing Station Apparatus

The drawing station is shown in Fig. 2.17. The oven includes two stainless steel pieces that are comprised of an outer surface to maintain the process temperature and an inner surface to shape the temperature field around the preform. Four heaters with a slightly curved surface of approximately 6 cm × 6 cm (Ceramic E-Mitters, CRS00009 from TEMPCO Electric Heater Corporation) were symmetrically placed between the two shells. The shape
of the temperature field affects the geometry of the resulting waveguide cross section. The square geometry of the oven follows the geometry of the preform and was specifically chosen to shape the temperature field to preserve the square cross section of the preform and fiber. The inner piece is a 24 cm tall hollow square tube with $6.5 \text{ cm} \times 6.5 \text{ cm}$, cross section and the outer piece has a $17 \text{ cm} \times 17 \text{ cm}$ cross section and 24 cm height. Pulling tension was provided by a DC powered collecting spool with a variable rotation speed. During fiber pulling, the preform was lowered using a vertical pico-motor driven translation stage to ensure proper preheating before pulling.

Figure 2.17. The draw tower is comprised of an oven and motion control for the preform and the drawn fiber. The oven has two hollow metal shells to contain and shape the temperature field with four (CRS00009) heaters positioned between the shells. A collecting spool maintains and regulates the drawn fiber and stores the final product. A pico-motor stage was used to keep the necking region of the preform at the correct height and temperature.
Fig. 2.18 shows the components of the drawing station. The temperature of the heaters are controlled by a variac as shown in Fig. 2.18(a). Fig. 2.18(b) shows the cross section of the oven comprised of two shells and four heaters sandwiched between the two shells. A DC powered wheel (Fig. 2.18(c)) provides the pulling tension. A pico-motor stage, shown in 2.18(d), lowers the preform inside the temperature field for preheating before fiber pulling.

Figure 2.18. (a) The variac controlling the input power of the heaters. (b) Four heaters are sandwiched between the inner shell and outer shell. (c) A DC powered motor provides a controlled pulling tension. (d) A pic-motor stage lowers the preform into the temperature field during the fiber drawing process.
The fiber was preheated at 152°C, below the TOPAS glass transition temperature of 160°C, for 180 minutes. The fiber was pulled at the rate of 1.6 cm/s after neck-down occurred at 257°C using a collecting spool with a variable rotation speed. A picture of preform neck-down is shown in Fig. 2.19. During fiber pulling the preform was lowered using a vertical pico-motor driven translational stage with the speed of 0.019 mm/s to ensure proper preheating. A final fiber thickness of 2 mm was achieved by empirically determining and controlling draw parameters such as temperature and pulling tension [43].

Figure 2.19. A preform necking down during the drawing process
Figure 2.20. Drawing process steps. First, the preform is preheated for 180 minutes. The preheat temperature is below TOPAS glass transition temperature ($160^\circ$). Then the temperature is quickly increased to above the glass transition temperature. The preform starts necking down after 40 minutes and is pulled to fabricate a fiber.

2.5. Characterization

Two sets of characterization were performed on fabricated samples. First, a physical characterization was done to ensure the fabricated fiber is similar to the design. Next, the successfully fabricated fibers were functionally characterized to test their performance.

2.5.1. Physical Characterization

Each fiber is characterized for thickness variation along its length as shown in Fig. 2.21.
Figure 2.21. A physical characterization example. Each fiber is characterized for thickness variation across its length. The cross section of each fiber at both ends is observed under a microscope to ensure eight holes along the fiber length.

A variety of waveguides with lengths ranging from 15 cm to 200 cm were successfully fabricated with a cross section of about $2 \text{ mm} \times 2 \text{ mm}$ and thickness variation ranging from 3.7% to 8.0% along waveguide lengths, as shown in Fig. 2.22 and Table 2.2.
Figure 2.22. Thickness variation of some fabricated samples along their lengths.

Table 2.2. Physical characteristics of several fabricated waveguides

<table>
<thead>
<tr>
<th>Fiber Number</th>
<th>Average Thickness [mm]</th>
<th>Thickness [(% variation)]</th>
<th>Length [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F150609b2</td>
<td>1.66</td>
<td>5.9</td>
<td>18</td>
</tr>
<tr>
<td>F150609b3</td>
<td>1.67</td>
<td>5.9</td>
<td>12</td>
</tr>
<tr>
<td>F150611a3</td>
<td>1.84</td>
<td>5.9</td>
<td>16</td>
</tr>
<tr>
<td>F150611d</td>
<td>2.51</td>
<td>5.6</td>
<td>14</td>
</tr>
<tr>
<td>F150611e</td>
<td>2.16</td>
<td>1.0</td>
<td>12</td>
</tr>
<tr>
<td>F150611g</td>
<td>3.2</td>
<td>6.6</td>
<td>24</td>
</tr>
</tbody>
</table>

Fig. 2.23 shows photographs of pulled fiber samples and cross section micrographs. Each fiber was polished with a 12 μm grit size lapping papers. Each fiber cross section was inspected to ensure all eight holes pass through the entire length of the fiber. Distortion is occasionally present in both sidewall and hole cross-sections as shown in Figs. 2.23 b-d.
Figure 2.23. (a) Fabricated waveguide samples. (b-c) Composite optical microscope images of fabricated waveguide cross sections of two different segments of fiber drawn from the same preform. (d) Composite optical microscope image of a fabricated waveguide cross section.

To study the effect of geometric distortion on the drawn fibers, simulations were designed to model the mode profile with breaks in symmetry. Fig. 2.24(a) shows the photographed cross section of a fabricated fiber and Fig. 2.24(b) shows the simulation at 230 GHz for the same fiber. The FDTD simulated mode was found to be well-confined to the core area despite these geometric imperfections.
Figure 2.24. (a) Micrograph of a fabricated waveguide cross section. (b) X-polarized mode propagation simulation for the fabricated waveguide considering all geometric imperfections at 230 GHz. The plot shows the magnitude of the electric field on a linear scale. Similar results were observed for y- polarization.

2.5.2. Functional Characterization

Two sets of functional characterization were done. First the output mode profile of the waveguide was mapped to ensure the beam is mostly confined to the core. Then, the fiber loss was measured.

Functional characterization was done using a vector network analyzer (VNA). The VNA used here was Agilent E8361C with the operation frequency of 10 MHz to 67 GHz. A pair of frequency extenders (OML V03VNA2-T/R) are used to operate in the range of 220 GHz to 325 GHz. A vector network analyzer measures four scattering parameters (S-parameters). $S_{11}$ and $S_{22}$ are the normalized reflected voltage signal to the incident beam. $S_{12}$ and $S_{21}$ are the normalized transmitted voltage signal to the incident beam. Fiber loss may be calculated using these parameters. The calibration and characterization experiments are
detailed in Appendix B.

2.5.2.1. Mode Mapping

The mode profile of a 30 cm long waveguide was mapped using a pinhole mode profilometer described in the following section. The setup consist of a VNA (Agilent E8361C) along with two frequency extenders (OML V03VNA2-T/R) at the transmitter and receiver ends. The VNA and extenders provided a source and detector for radiation from 220 GHz to 325 GHz. The waveguide was placed on an x-y-z stage with tilt stages between the two frequency extenders allowing proper alignment of the source into the fabricated waveguide. A 250 μm pinhole was mounted to the receiver module, which was then stepped in an x-y array to map the transmitted mode from the fiber in steps of 250 μm.

Fig. 2.26 shows the resulting transmitted ($S_{12}$) mode profile of the fabricated waveguide averaged over the frequency range of 220 GHz to 325 GHz. Transmission in the fiber core was measured to be 10 dB higher than near the edges of the waveguide. Notably, this is a relative measurement; data do not represent exact transmission values. The pinhole profilometer technique provides an imaging measurement consistent with the FDTD simulation of Fig. 2.24(b).
Figure 2.25. The profilometer setup. The VNA and extenders provided a source and detector for radiation from 220 GHz to 325 GHz. The waveguide was placed on an x-y-z stage with tilt stages between the two frequency extenders allowing proper alignment of the source into the fabricated waveguide. A 250 µm pinhole was mounted to the receiver module, which was then stepped in an x-y grid array to map the transmitted mode from the fiber in steps of 250 µm.
2.5.2.2. Fiber Loss Measurements

The setup consists of a VNA (Agilent E8361C) along with two frequency extenders (OML V03VNA2-T/R) at the transmitter and receiver ends. The VNA and extenders provide a source and detector for radiation from 220 GHz to 325 GHz as shown in Fig. 2.27. To ensure efficient coupling, a custom built gold plated taper with a WR-03 aperture is connected to the modules and tapered to 1.3 mm × 1.3 mm aperture size (comparable to the waveguide core size) to couple THz waves into the fiber core. A WR-03 horn (with 25 dB gain) with aperture size of 7.00 mm × 5.84 mm couples the wave out of the fiber efficiently while connected to WR-03 modules on the transmitter side. A fabricated fiber mounted on x-y-z stages at both ends was aligned for maximum transmission.
Figure 2.27. Fabricated waveguide under test for loss. Efficient coupling into waveguide using a custom made taper with 1.3 mm × 1.3 mm aperture size. Efficient coupling into receiver from waveguide using a WR-03 horn antenna with aperture size of 7.00 mm × 5.84 mm.

Each fiber was tested five times with fiber loss consistent across all measurements. Transmission and reflection at both ends of the fiber were measured. The reflection at the transmitter-air and receiver-air interfaces are measured to obtain reflection coefficients at the fiber-air interference. Fiber loss was calculated using the formula
\[ E_{\text{output}}(\omega) = E_{\text{input}}(\omega)T_1T_2C_1C_2 \exp(-\alpha L/2) \exp(-j\beta L). \quad (2.18) \]

Here, the transmitted electric field \( E_{\text{output}}/E_{\text{input}} \), is the same as \( S_{12} \). \( T_1 \) and \( T_2 \) are the transmission from each surface of the fiber and may be calculated using \( 1 - S_{11} \). Coupling coefficients, \( C_1 = C_2 = 1 \) is considered since the taper and horn antennas are used for efficient coupling.

Three samples with three lengths were tested. The following is the fiber loss result for each sample. Each sample is named according to the date it was drawn and the segment of the fiber from which was taken. The physical characteristics of each sample are given in Table 2.3.

<table>
<thead>
<tr>
<th>Fiber number</th>
<th>Average thickness [mm]</th>
<th>Thickness variation [percent]</th>
<th>Length [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F150611d</td>
<td>2.509</td>
<td>5.6</td>
<td>12</td>
</tr>
<tr>
<td>F150611a21</td>
<td>2.284</td>
<td>6.78</td>
<td>19</td>
</tr>
<tr>
<td>F150611c</td>
<td>2.303</td>
<td>3.8</td>
<td>30</td>
</tr>
</tbody>
</table>

2.5.2.3. Sample F150611d

The physical characteristics of the sample F150611d is given in Table 2.3. The measurement setup is shown in Fig. 2.28. One x-y-z stage was used due to the short length of the fiber. A THz wave is coupled into the fiber using the taper and coupled out using the horn antenna. The fiber was aligned for maximum transmission using the x-y-z stage. Measurements were repeated five times.
Fig. 2.29 shows the calculated fiber loss taken from measured S-parameters. Detailed calculations can be found in Appendix B. The average fiber loss was calculated across the frequency range for each measurement and collected in Table 2.4. The fiber loss was inconsistent across the measured values. This may be due to the short length of the fiber. A longer sample was chosen (F150611a21) for the next measurement.
Table 2.4. Fiber loss measurements of sample F150611d.

<table>
<thead>
<tr>
<th>number of measurements</th>
<th>$S_{12}$</th>
<th>$S_{12}$ [dB]</th>
<th>$T_1^2$</th>
<th>$T_2^2$</th>
<th>$S_{12}$ [dB/cm]</th>
</tr>
</thead>
<tbody>
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<td>0.96</td>
<td>0.96</td>
<td>-0.68</td>
</tr>
<tr>
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<td>0.95</td>
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<td>0.95</td>
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<td>-7.43</td>
<td>0.96</td>
<td>0.97</td>
<td>-0.59</td>
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</tbody>
</table>

2.5.2.4. Sample F150611a21

A 19 cm fiber was chosen for loss measurement. Table 2.3 shows the physical characteristics of the fiber.

The measurement setup is shown in Fig. 2.30. Here, two x-y-z stages were used for alignment. The wave is coupled into the fiber using the taper and coupled out using the horn antenna. The fiber was aligned for maximum transmission using the x-y-z stages. Each measurement was done five times.

Figure 2.30. Fiber (F150611a21) characterization setup.
Fig. 2.31 shows the calculated fiber loss taken from measured S-parameters. The average fiber loss was calculated across the frequency range for each measurement and shown in Table 2.5. The fiber loss was more consistent across the measured values compared to fiber F150611d. A longer fiber (F150611c) was chosen for the next experiment to achieve more repeatable results.

![Figure 2.31. Fiber loss for sample F150611a21 is calculated using measured S-parameters.](image)

<table>
<thead>
<tr>
<th>number of measurements</th>
<th>$S_{12}^2$</th>
<th>$S_{12}$ [dB]</th>
<th>$T_{11}^2$</th>
<th>$T_{22}^2$</th>
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</tr>
</tbody>
</table>
2.5.2.5. Sample F150611c

A 30 cm fiber was chosen for loss measurement. Table 2.3 shows the physical characteristics of the fiber.

The measurement setup is shown in Fig. 2.32. Here two x-y-z stages were used for alignment. The wave is coupled into the fiber using the taper and coupled out using the horn antenna. The fiber was aligned for maximum transmission using the x-y-z stages. Each measurement was done five times.

![Figure 2.32. Fiber (F150611c) characterization setup.](image)

Fig. 2.33 shows the calculated fiber loss taken from measured S-parameters. The average fiber loss was calculated across the frequency range for each measurement and shown in Table 2.6. The measured losses were consistent across the measured values and the experiment was repeatable for this fiber length. The fiber shows an average 0.24 dB/cm loss. Notably, TOPAS material loss is 0.22 dB/cm at 250 GHz.
Figure 2.33. Fiber loss for sample F150611c is calculated using measured S-parameters.

Table 2.6. Fiber loss measurements of sample F150611c.

<table>
<thead>
<tr>
<th>number of measurements</th>
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<th>( S_{12} ) [dB]</th>
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<th>( T_{2}^{2} )</th>
<th>( S_{12} ) [dB/cm]</th>
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<td>0.11</td>
<td>-9.70</td>
<td>0.76</td>
<td>0.79</td>
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</tr>
</tbody>
</table>
Chapter 3

VORTEX THZ WAVEGUIDE

3.1. Introduction

Although THz waves enable higher chip-to-chip data transfer rates compared to RF, there is ever a need for higher capacity. To increase the communication capacity and data transfer rate, different methods such as polarization division multiplexing (PDM), time division multiplexing (TDM), wavelength division multiplexing (WDM), and space division multiplexing (SDM) are used [44]. Square cross-section waveguides presented in the previous Chapter were developed for PDM applications. SDM using orbital angular momentum has recently gained interest in free-space millimeter-waves [45] as well as optical free-space and fiber optic communication systems [46].

Electromagnetic radiation carries both energy and momentum. Momentum has a spin component related to polarization and an orbital component related to spatial distribution. In 1992 Allen, et al., demonstrated that a Laguerre-Gaussian laser mode has an orbital angular momentum (OAM) greater than the spin angular momentum. They showed that OAM in a beam of light with an azimuthal phase dependence, \( \exp(i\ell \phi) \) with \( \ell \) the azimuthal index, can be converted to mechanical torque [47]. Beams endowed with OAM have helical phase distributions and annular intensity profiles in the azimuthal plane. Fig. 3.1 shows the beam intensity of a Gaussian profile and the first five OAM beams generated at 543 nm in our lab by Mehdi Nouri. A detailed experimental measurement setup can be found in [48].
Figure 3.1. The measured intensity profiles of a generated OAM endowed Gaussian beam at 543 nm. (a) A Gaussian beam. (b) A first order OAM beam ($\ell = 1$). (c) A second order OAM beam ($\ell = 2$). (d) A third order OAM beam ($\ell = 3$). (e) A fourth order OAM beam ($\ell = 4$). (f) A fifth order OAM beam ($\ell = 5$). Measurements were done by Mehdi Nouri [48].

The orthogonality of OAM beams having different $\ell$ allows SDM with low crosstalk [49], [50], [51], provided the propagation channel supports the mode set and preserves orthogonality of the modes. Optical communication links have achieved Tbits/s capacities using multiplexed OAM beams. OAM beams have been generated using arrayed waveguide gratings [52], computer generated holograms [53] and continuous spiral phase plates [54]. Optical
OAM beams have been generated from Hermite-Gaussian beams using an astigmatic optical system [47]. Alternatively, spatial light modulators (SLMs) are used to generate OAM beams [55]. A set of SLMs can be used to losslessly demultiplex OAM beams, by transforming the azimuthal position of an input beam to the transverse position of an output beam [55]. Since SLMs do not extend into the sub-THz and RF, spiral phase plates greatly extend the operating spectral range of OAM beams. Recently, OAM beams were experimentally generated using metamaterials [45]. THz OAM beams have also been demultiplexed using two 3D printed diffractive elements [56].

OAM optical communications began in free space channels [49]. OAM transmission in an optical fiber was first studied in the 1990s [57]. Graded index fibers with an inverse parabolic refractive index profile were demonstrated to support two OAM orders around 1550 nm [58]. Air core step index fibers were demonstrated for stable transmission of multiple OAM modes in an optical fiber at 1530 nm [59]. Air core microstructure ring fibers were introduced recently for OAM optical transmission around 1550 nm [60]. The first numerical studies of a hollow core THz waveguide were recently done by Li, et al., in the frequency range of 0.2 -0.9 THz [61].

In this Chapter, a novel square cross section holey core/cladding vortex dielectric waveguide for submillimeter SDM applications is presented. The waveguide is designed for sub-THz chip-to-chip communication applications. Here, the design, fabrication, and verification of dielectric vortex sub-THz waveguides and discrete-step spiral phase plates for sub-THz OAM generation are presented. The waveguide, designed to support the first two order OAM-endowed Laguerre Gaussian beams (Fig. 3.1) using a hollow core, combines benefits of a low-loss material (TOPAS cyclic olefin copolymer) with a holey cladding configuration as a vortex waveguide. Sub-THz OAM beams propagated in dielectric waveguides allow guided high capacity communication. The waveguides were tested and shown to successfully transmit the first order OAM beam at 280 GHz. In this work, OAM beams were generated using a low cost discrete step spiral phase plate with low material loss. This design represents an easily fabricated phase plate for OAM generation at 280 GHz.
3.2. Design and simulation

A square waveguide geometry was chosen to robustly support both horizontal and vertical states of polarization for low crosstalk PDM. A square geometry, as shown in the previous Chapter, shows good mode confinement despite fabrication defects and breaks in symmetry.

Fibers having a high index ring distribution are used for OAM transmission since the index profile is similar to an OAM beam profile [62]. This allows for multiple Laguerre-Gaussian modes to propagate in the same physical channel. This increases data transfer capacity using spatial division multiplexing. Air core fibers are a common method to create a high index ring distribution and confine the mode to the larger index step between the central hole and cladding [63]. In this work, a hole pattern is used to lower the index of the cladding and define the core. The single-dielectric holey cladding architecture provides a low loss waveguide that is relatively simple to fabricate compared to doped waveguides.

Finite-difference-time-domain (FDTD) simulations were done across a sweep of hole sizes and a wide range of configurations using the BeamPROP package in RSoft. The relative size of a hole compared to the wavelength determines whether the mode takes shape inside the holes or in the dielectric. This information was used to design and simulate holey core/cladding waveguides. To create a null in the center for the frequency range of 200 GHz to 300 GHz, a minimum 400 μm diameter hole is needed. Cladding hole sizes range from 300 μm to 1100 μm depending on hole configurations. Different hole configurations were investigated, including a 9-hole pattern and a 21-hole pattern. The hole sizes and configurations were varied to confine the mode between the central hole and cladding holes. A 4 mm × 4 mm square waveguide with a 400 μm diameter hole in the center of the fiber and an 8-hole cladding array with alternating 1100 μm and 800 μm diameters, shown in Fig. 3.2, was chosen for this work.
Fig. 3.2. The cross section of the designed vortex waveguide. The square waveguide is 4 mm × 4 mm with a 400 µm central hole and an 8-hole cladding array with alternating 1100 µm and 800 µm diameters.

Fig. 3.3 shows simulation results of the designed waveguide. These particular hole dimensions represent a combination of good theoretical performance and manufacturability. The reported central hole size is a balance between good performance and higher fabrication yield. The cladding hole sizes are selected to confine the mode to the waveguide core while shaping a circular mode profile. A steady-state simulation, Fig. 3.3(a), shows the output electric field magnitude and 3.3(b) the phase information of a 280 GHz plane wave propagating through the designed vortex fiber. The material refractive index of the fabricated fiber is 1.5258. Fig. 3.3(c) and 3.3(d) show the amplitude and phase information of a launched ($\ell=1$) OAM beam, respectively. Simulations of the designed fiber demonstrates the successful transmission of an OAM beam while preserving the phase characteristics of the beam. The designed fiber operates in the frequency range of approximately 200 GHz to 300 GHz.
The dimensions of the waveguide are designed to support helicities $\ell = 1$ and 2, which yield an increasing inner-to-outer radii ratio. These are measured from the beam center to the first and second full width at half max (FWHM) of their radial intensity profiles.

Figure 3.3. A FDTD convergence study of a fiber at 280 GHz. A center hole of 400 $\mu m$ diameter and cladding holes with 1100 $\mu m$ (corners) and 800 $\mu m$ (sides) diameters are outlined with circles. Two different launching conditions are simulated. (a) Magnitude and (b) phase of the output electric field as a plane wave is launched into the fiber. (c) The simulated magnitude and (d) phase of the electric field using a launched first order OAM beam. Linear scale electric field magnitude shows an annulus with inner radius of approximately 400 $\mu m$ and outer radius of 800 $\mu m$. 
At any distance from the center of the waveguide, the averaged refractive index was calculated as a weighted average of air holes and dielectric material (TOPAS). Circular contours are used for conventional circular fibers. Here, square contours shown in the inset of Fig. 3.4 are chosen to match the geometry of the waveguide. Parameter \( s \) is defined as the half width of the square contours. The average refractive index was calculated using the line integral

\[
n = \sum (n_{\text{air}}f_{\text{air}} + n_{\text{TOPAS}}f_{\text{TOPAS}}) \tag{3.1}
\]

where \( n \) is the refractive index of the material, and \( f \) is the linear fraction covered by the material. The refractive index of the holey waveguide is the weighted average of the core and cladding. The latter consists of air holes and TOPAS.

The calculated average refractive index of the waveguide as a function of \( s \) is plotted in Fig. 3.4. The beam is mostly confined between the center air hole and the ring of air holes to satisfy the boundary conditions.
Figure 3.4. Averaged refractive index of the designed waveguide as a function of square contours. Refractive index of the waveguide is 1 ($n_{\text{air}}$) from $s=0$ to $140 \, \mu m$, then increases as the width of the contour increases. At $s=800 \, \mu m$ the refractive index decreases due to air holes. The refractive index is the same as the TOPAS refractive index around $s=1900 \, \mu m$ since there are no air holes in this region. An OAM beam is mostly confined between the central hole and the cladding holes. (Inset) Cross section of the designed vortex fiber showing a square contour with parameter $s[\mu m]$. The waveguide has a 4 mm $\times$ 4 mm cross section with a center hole of 400 $\mu m$ diameter and cladding holes with 1100 $\mu m$ and 800 $\mu m$ diameters.

3.2.1. Higher order OAM studies

A second order OAM beam was launched into the same designed waveguide (Fig. 3.3) at 280 GHz. Fig. 3.5 (a) shows the mode is well-confined to the core. As shown in Fig. 3.5 (b), the phase is more distorted compared to the first OAM beam (Fig. 3.3(d)). This is due to the fact that the outer radius of the OAM beam increases in size as $\ell$ increases, resulting in more distortion around air holes.
Figure 3.5. A FDTD convergence study of a fiber at 280 GHz. A 400 µm diameter center hole and 1100 µm (corners) and 800 µm (sides) cladding holes are outlined with circles. A second order OAM beam was launched into the fiber. (a) Magnitude and (b) phase of the electric field demonstrate that the designed fiber supports an $\ell=2$ OAM beam.

The effect of waveguide core size on output power of the fiber was studied using an advanced finite-difference beam propagation (FD-BPM) technique in the RSoft simulation package. Fig. 3.6 shows a normalized power loss [dB/cm] for $\ell=1$, $\ell=2$ OAM beams launched into waveguides with the same hole configuration as the designed waveguide (Fig. 3.3) and different core sizes. Some differences were observed between the two launching conditions, $\ell=1$ and $\ell=2$. As expected, the second order OAM beam propagates in larger core sizes. In addition, power loss is higher for the second order OAM compared to the first order OAM up to $s/s_0=1.25$. After this point, the power loss is a constant 0.236 dB/cm since the wave is mostly confined to the core and losses are due to material (0.22 dB/cm), scattering, and coupling losses. For a constant launched OAM order (e.g. $\ell=1$), the power loss decreases as the size of the core increases. This is expected since the mode is more confined to the core. Hence, less power is lost due to leaking.
The effective refractive index dependence on core size is plotted in Fig. 3.6. As shown, the effective refractive index decreases as \( \ell \) increases, since the beam profile is larger and closer to the cladding holes. For a constant launched OAM beam order, the effective refractive index increases as the core size increases since the beam is more confined to the core that is mostly comprised of TOPAS.

### 3.3. Fabrication

Processes used to fabricate holey core and holey cladding fibers include tube stacking, micro-structured molding, and a drill-and-draw technique [42]. The drill and draw technique was chosen here due to its simplicity for holey fibers having few holes. TOPAS COC (Advanced Polymer Company) was used because its material loss at 0.3 THz (0.2dB/cm [28]) is
lower than other commonly used dielectric materials as was shown in Table 2.1.

The drill and draw fabrication process consists of three steps: preform fabrication, hole definition, and heated fiber drawing from preform.

3.3.1. Preform Fabrication

A 35 mm × 35 mm × 90 mm TOPAS block was cast by incrementally adding 10 layers of TOPAS beads (20 ml for each layer) every 20 minutes at 210°C to a preheated (157°C on a hotplate) stainless steel mold. Boron nitride was sprayed on the mold sidewalls as an anti-sticking agent prior to use. The preform was annealed in a 230°C convection oven for 40 minutes. The temperature and steps of preform fabrication were chosen to form a uniform block of TOPAS. The cross sectional dimension is calculated and experimentally determined based on preform-to-fiber shrink ratios. Slight thickness variations can be fine-tuned later in the drawing process by other parameters such as temperature and pulling tension [43]. The height of the preform is chosen to have sufficient material for fiber drawing. A preform fabrication process is shown in Fig. 2.15.

3.3.2. Hole Definition

Holes were precisely drilled into the preform at their design-specified locations (9.2 mm center-to-center pitch for cladding holes and 12.6 mm from corner hole centers to the core center) using a mechanical drill press and drill bit sizes of 1/4”, 7/32” and 7/64”. The hole-drilling process was done very slowly using WD-40 spray as lubricant to ensure visually smooth holes in the drawn fiber. The preform was soaked in a soapy water solution for a day to remove any remaining WD-40 residue that may contribute to loss.
3.3.3. Heated Fiber Drawing

Waveguides were drawn from TOPAS preforms using a custom built drawing station described in section 2.4.3.1. The oven was designed with a square cross section to preserve the square geometry of the fiber. The oven includes two stainless steel shells, a 17 cm × 17 cm × 24 cm outer shell to stabilize drawing temperature and a 6.5 cm × 6.5 cm × 24 cm inner shell with square geometry to shape the temperature field across the preform. Four 6 cm × 6 cm ceramic heaters (Ceramic E-Mitters, CRS00009 from TEMPCO Electric Heater Corporation) are symmetrically sandwiched between the two oven surfaces. The fiber was allowed to free fall after neck-down at 495°C to yield a thickness of 4 mm × 4 mm.
3.4. Characterization

Two types of characterizations were performed. First, a physical characterization to ensure the fabricated fiber is as designed. Next, the successfully fabricated samples were tested for first order OAM beam transmission.

3.4.1. Physical Characterization

A variety of 10 cm to 45 cm fiber lengths were fabricated with average thickness of 4 mm × 4 mm having thickness variation of 0.9 to 7% along the fiber lengths. Fig. 3.8 shows some fabricated samples. Fig. 3.8(a) and Fig. 3.8(b) show the cross section of fabricated vortex fibers.

Each fiber was characterized for thickness variation along its length and the hole dimensions. Table 3.1 shows the physical characterization result for some fabricated fiber samples. Fig. 3.9 shows the thickness variation of some samples along their lengths.

<table>
<thead>
<tr>
<th>Fiber number</th>
<th>Average thickness [mm]</th>
<th>Thickness % variation</th>
<th>Length [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F160412c</td>
<td>3.86</td>
<td>1.3</td>
<td>12</td>
</tr>
<tr>
<td>F160412d</td>
<td>4.4</td>
<td>0.89</td>
<td>14</td>
</tr>
<tr>
<td>F160405c</td>
<td>2.3</td>
<td>2.2</td>
<td>18</td>
</tr>
</tbody>
</table>
Figure 3.8. (a)-(b) Cross section of fabricated vortex fibers. (c) Some fabricated samples measured for thickness variation.
Figure 3.9. Thickness variation of some fabricated vortex fibers along their length.

As shown in Fig. 3.8 (a) and (b), distortion and symmetry breaks are present due to fabrication. The as-fabricated square fiber shown in Fig. 3.8(b) was simulated to study the effect of fabrication distortions on fiber performance. Fig. 3.10 shows the converged simulations of a first order 280 GHz OAM beam launched into the fabricated waveguide. Figure 3.10(a) shows good mode confinement despite physical defects. The phase plot shown in Fig. 3.10(b) shows the phase information at the output end of the fiber. The OAM characteristic of the beam is well-preserved despite fabrication imperfections. Additionally, a power loss simulation study was done with the first order OAM beam launched into the waveguide. The normalized output power showed a 0.24 dB/cm power loss for the fabricated waveguide.
3.4.2. Functional Characterization

A successfully fabricated waveguide was tested for the first order OAM transmission. A stepped spiral phase plate was fabricated to generate the OAM beam from a plane wave. A first order OAM beam was generated after a plane wave, generated by the VNA, passed through the fabricated phase plate. In this section, the stepped spiral phase plate fabrication is discussed, the generated OAM beam is mapped experimentally, and results of OAM beam transmission through the fabricated fiber are presented.

3.4.2.1. Phase Plate Fabrication

An experiment of characterization called for the generation of an OAM input beam. To this end, a novel stepped spiral phase plate was fabricated. A total phase plate thickness, $h = 2.035$ mm for refractive index, $n = 1.5258$ was calculated to create a $2\pi$ phase shift at
280 GHz for the first order mode ($\ell = 1$) using [54]

$$h(\phi) = \frac{\phi}{2\pi} \frac{\ell \lambda}{n - 1}.$$  \hspace{1cm} (3.2)

To create the phase shift, a stack of eight 0.254 mm thick TOPAS sheets (provided by Advanced Polymers Company, TOPAS-8007) was used to form a stepped spiral phase plate. First, eight 30 mm $\times$ 30 mm sheets were cut by hand using a utility blade. A pie piece of each sheet was cut out with 40° sequences in the azimuthal direction. All eight sheets were aligned using a protractor with 1° precision and stacked. The steps were secured by double sided tape positioned in the corners of each plate, out of the field of the coupled beam. Fig. 3.11 shows a 30 mm $\times$ 30 mm fabricated phase plate.

Figure 3.11. To generate an OAM beam, a novel phase plate is made by stacking eight layers of TOPAS sheets to make a total $2\pi$ phase shift across the azimuthal angle of the beam at 280 GHz. The discrete spiral phase plate has 30 mm $\times$ 30 mm width and $h = 2.032$ mm overall thickness.
3.4.2.2. OAM Generation and Mapping

The characterization setup (Fig. 3.12) includes a vector network analyzer (Agilent E8361C) along with frequency extenders (OML V03VNA2-T/R) as a source for radiation at 280 GHz. A custom built taper with aperture of 1.3 mm × 1.3 mm was connected to the transmitter module to propagate a wave with ∼ 1 dB variation across a 7 mm × 7 mm transverse plane located 8.5 cm from the source. The fabricated stepped spiral phase plate (Fig. 3.11) was placed 8.5 cm from the transmitter.

The receiver module includes a frequency extender (OML V03VNA2-T/R) mounted on an x-z stage. A 1.3 mm × 1.3 mm taper, similar to the taper on the transmitter, was mounted on the receiver module to map the two dimensional mode profile in 1 mm steps.

To ensure the phase plate generates an OAM beam, the mode profile was mapped (Fig. 3.12) 1.2 cm from the phase plate. The mapped mode profile is shown in Fig. 3.13. The beam profiles shown herein are these data with a linear interpolation between measurement points. A center null (transmission loss of -60 dB) is due to the destructive interference of the beam generated by the phase plate. The null is surrounded by ∼ 25 dB higher transmission ring of the Laguerre-Gaussian beam.
Figure 3.12. Experimental setup to map the mode profile of the generated OAM using the fabricated phase plate
Figure 3.13. Mapped mode profile of the beam 1.2 cm after the phase plate at 280 GHz. The null in the center represents the destructive interference pattern created by the phase plate. The null is surrounded by a 25 dB higher transmission ring of the Laguerre-Gaussian beam.

3.4.2.3. Experimental Setup

The same profilometer setup was used to characterize the fiber as shown in Fig. 3.14. The fabricated phase plate was placed 8.5 cm from the transmitter. A 10 cm-long fabricated vortex fiber was mounted on an x-y-z stage placed 0.13 mm from the first spiral phase plate and 3.5 mm from the receiver. The amplitude of the transmitted beam does not show the phase characteristics of the beam. Thus, to investigate the phase information of the beam,
the technique used by Ren, et al., [64] and Yan, et al., [54] to confirm the OAM characteristics of the beam was used. In this technique, an OAM beam with helicity of \(+\ell\) is passed through a spiral phase plate or an SLM with a \(-\ell\) value to unwind the OAM beam into a plane wave.

Figure 3.14. Mode profilometer setup. A vortex fiber is placed between a receiver and transmitter frequency modulator (280 GHz) connected to the vector network analyzer. A spiral phase plate (SPP1) placed after the transmitter generates an OAM beam, and the second spiral phase plate (SPP2) unwraps the OAM beam to a plane wave. A taper with 1.3 mm \(\times\) 1.3 mm aperture at the receiver is stepped across the cross section of the waveguide to map the profile of the mode.
Figure 3.15. Experimental setup for the first order OAM transmission using a fabricated vortex fiber. Note: photo was taken while the receiver was mapping the beam profile.

To confirm that the beam carries OAM, another spiral phase plate (SPP2 in Fig. 3.14) perfectly matched with the first phase plate, was placed in the output of the fiber, 1.5 mm from the receiver. The second phase plate is vertically inverted with respect to the first phase plate so the net optical path within two phase plates is the same at every point in the azimuthal plane. A plane wave is expected to be mapped after the second phase plate [54].

In the experimental characterization setup (Fig. 3.15), a 280 GHz plane wave hits the first phase plate to generate a first order ($\ell=1$) Laguerre-Gaussian mode. The doughnut shaped mode is guided through the vortex fiber. The second phase plate unwinds the phase shift of the beam and converts an OAM beam to a plane wave. The taper, connected to the
receiver, is used to map the mode within a 7 mm × 7 mm azimuthal area in 1 mm steps.

3.4.2.4. Result

The beam profile was mapped after passing through each component. First, the beam profile was measured in the azimuthal plane 8.5 cm from the 280 GHz source as shown in Fig. 3.16(a) shows ∼1 dB variation across a 7 mm × 7 mm area. Next, the fabricated phase plate was placed 8.5 cm from the source, and the resulting beam profile measured at 0.5 mm from the phase plate was mapped in a 7 mm × 7 mm area to emphasize the doughnut shape of the beam as shown in Fig. 3.16(b). This shows the beam profile coupled in the vortex fiber. The data is presented to emphasize the important null in the center of the OAM beam. The null in the center of the beam decreased by 15 dB with respect to the overall beam profile that demonstrates destructive interference of the beam due to a rotationally dependent phase shift caused by the phase plate. This drop in intensity is large enough to not be mistaken with absorption or scattering by the phase plate. Uniform beam intensity around the dark center also confirms negligible material absorption or scattering due to the phase plate. The doughnut-shaped mode was transmitted using a fabricated submillimeter vortex fiber.

Fig. 3.16(c) shows that the annular shape of the beam profile was preserved at the output of the vortex fiber. Our results indicate some degradation of the beam due to fabrication imperfections. For example, Fig. 3.16(c) shows a slight beam deformation at the output of the fiber. These imperfections appear to increase loss as well. By comparing the power between Fig. 3.16(b) and Fig. 3.16(c) the total loss due to coupling and propagation may be estimated to be 12 dB. The numerical analysis of Fig. 3.16, indicates a ∼0.25 dB/cm attenuation. The experiment was designed to emphasize OAM propagation and was not optimized for loss. As a result, coupling loss is high. However, it is unlikely that the coupling loss accounts for the entirety of the remaining 9.5 dB loss, and some of this excess loss is attributed to fabrication imperfections.
Referring to Figure 3.3, phase information is needed to distinguish an annular beam from an OAM-endowed beam. The OAM nature of the transmitted beam was verified by including a vertically inverted second phase plate for the special case of an input $\ell=1$ OAM beam. This element unwinds the helical plane back to a planar phase front. Therefore, to investigate the OAM content of the beam a vertically inverted phase plate was placed at the output of the vortex fiber. The transmitted profile was mapped as shown in Fig. 3.16(d). At all points except $(x=4\,\text{mm},\,z=4\,\text{mm})$, an 8 dB signal drop was measured. This is due to absorption and scattering by the second phase plate. Importantly, a transmission increase of 7 dB is observed at $(4,\,4)$, the dark center in Fig. 3.16(b)-(d), demonstrating that the second phase plate corrected the phase shift caused by the first phase plate. This demonstrates the successful transmission of an $\ell=1$ sub-THz Laguerre-Gaussian beam carrying orbital angular momentum through the holey dielectric vortex fiber.
Figure 3.16. Transmission signal mapped at four positions in the beam line of Fig. 3.14. (a) The beam profile at 8.5 cm from source before entering the first phase plate shows a uniform beam with $\sim 1$ dB variation. (b) The mapped beam after passing through the first phase plate shows a null in center and a surrounding ring with higher intensity. This is the beam before entering the vortex fiber. The data is presented to emphasize the important null in the center of the generated OAM beam. (c) The mode profile at the output of the fiber showing a central null. (d) The transmitted mode, mapped after passing the second phase plate, shows an enhancement in the center null while other points have not experienced significant change. The beam is returned to an essentially uniform, albeit attenuated profile.
Chapter 4

LOSS REDUCTION STRATEGIES

The square holey cladding waveguide presented in Chapter 2 showed an average measured fiber loss of 24 dB for a 1 m length. Considering the TOPAS material loss of \( \sim 22 \text{ dB/m} \), the fiber loss is mainly due to the material loss in the fiber core. To further lower the fiber loss, two strategies were investigated. The first strategy is loss reduction using lower loss materials. The second strategy is loss reduction using a low loss fiber geometry.

4.1. Low Loss Materials

As shown in Table 4.1, Teflon, quartz, fused silica, and co-polymer polypropylene are some options with lower material loss. However, advanced fabrication and safety facilities should be considered for these materials. Fused silica results in a loss improvement factor of 1.2 over TOPAS. Co-polymer polypropylene represents a factor of 1.4 loss improvement. Teflon and quartz represent the lowest material loss in the frequency range of interest. A loss reduction factor of 2.4 and 4 may be achieved using Teflon and quartz, respectively.

<table>
<thead>
<tr>
<th>Material</th>
<th>0.2 THz</th>
<th>0.3 THz</th>
<th>0.5 THz</th>
<th>1 THz</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOPAS [28]</td>
<td>0.19</td>
<td>0.24</td>
<td>0.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Fused silica [38]</td>
<td>0.10</td>
<td>0.20</td>
<td>0.33</td>
<td>1.5</td>
</tr>
<tr>
<td>Polypropylene, Co-Polymer (PP) [36]</td>
<td>0.10</td>
<td>0.17</td>
<td>0.26</td>
<td>0.74</td>
</tr>
<tr>
<td>Teflon (PTFE) [20]</td>
<td>0.07</td>
<td>0.10</td>
<td>0.40</td>
<td>2.17</td>
</tr>
<tr>
<td>Quartz [38]</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
<td>0.35</td>
</tr>
</tbody>
</table>
4.2. Low Loss Geometries

Though a low loss material may be chosen, further loss reduction is expected if some regions of the core could be replaced with air holes. The low loss holey geometries discussed in this section were inspired by the designed vortex fiber discussed in Chapter 3. The objective is to design a fiber whose geometry allows the propagation of a plane wave with lower loss. Fig. 4.1 shows the output mode profile of the same vortex fiber presented in Chapter 3, previously designed for the propagation of OAM endowed L-G beams. Here, however a plane wave propagates through the vortex fiber with the same hole sizes and geometry. As shown in Fig. 4.1, some portion of the beam propagates through the 400 µm central hole.

![Figure 4.1. A plane wave propagating in the previously designed vortex fiber for OAM endowed L-G beams. A portion of the beam traveling through the central hole is subject to low loss transmission.](image)

By optimizing the hole size in both the core and cladding, the majority of the beam may travel in the central hole. The relative size of the core and cladding holes compared to the
wavelength determine whether the mode takes shape inside the holes or in the dielectric. This results in a low loss transmission of the beam in the core while the holey cladding acts as a boundary condition to force the beam into the core. Here, three broadband holey core/cladding waveguides operating at 180 GHz to 360 GHz are presented for low loss PDM applications. Note, the presented designs are broadband. Lower fiber loss may be achieved if the design is fine-tuned for a narrow bandwidth.

4.2.1. Single Central Hole Design

The first waveguide design, shown in Fig. 4.2, is 1300 \( \mu \text{m} \times 1300 \mu \text{m} \) in size. Eight 300 \( \mu \text{m} \) diameter holes form the cladding and a single 200 \( \mu \text{m} \) diameter central hole creates a holey core. Simulations demonstrate that the waveguide is broad-band (from 180 GHz to 360 GHz) and supports both vertical and horizontal states of polarization.

The loss improvement with the single central hole design, compared with the original holey core waveguide discussed in Chapter 2, is shown in Table 4.2. A loss improvement factor of 1.3 is demonstrated with this design.

Table 4.2. Fiber loss comparison between the original design discussed in Chapter 2 with the proposed single hole design.

<table>
<thead>
<tr>
<th>Loss comparison</th>
<th>Original design</th>
<th>Proposed design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated loss (270 GHz)</td>
<td>0.22 [dB/cm]</td>
<td>0.15 [dB/cm]</td>
</tr>
</tbody>
</table>
Figure 4.2. A holey core/cladding design with eight 300 \( \mu \text{m} \) diameter cladding holes and a single 200 \( \mu \text{m} \) diameter central hole is investigated to lower the loss. Simulations were done for vertical and horizontal states of polarization at (a),(b) 360 GHz and (c),(d) 180 GHz.

As shown in Fig. 4.2 some portion of the beam travels in the dielectric filled region of the core. This contributes to the fiber loss. A second holey core fiber with more holes in the center was designed to decrease the loss.
4.2.2. Nine Central Hole Design

The fiber design shown in Fig. 4.3 is a $2300 \mu m \times 2300 \mu m$ waveguide with eight $550 \mu m$ diameter holes in the cladding. The core of the waveguide is comprised of eight $300 \mu m$ diameter holes surrounding a $200 \mu m$ diameter central hole. The broadband transmission of 180 GHz to 360 GHz is supported by the fiber for both horizontal and vertical states of polarization.

The loss improvement from this design is 1.5 times better than the original holey core waveguide discussed in Chapter 2 as shown in Table 4.3. However, the fabrication yield for this design is lower due to the greater number of holes, while the loss improvement is not significant.

Table 4.3. Fiber loss comparison between the original design discussed in Chapter 2 with the proposed nine central hole design.

<table>
<thead>
<tr>
<th>Loss comparison</th>
<th>Original design</th>
<th>Proposed design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated loss (270 GHz)</td>
<td>0.22 [dB/cm]</td>
<td>0.14 [dB/cm]</td>
</tr>
</tbody>
</table>
Figure 4.3. A holey core/cladding design with seventeen holes (550 µm, 300 µm, and 200 µm hole diameters) for loss improvement simulated to support vertical and horizontal states of polarization at (a),(b) 360 GHz and (c),(d) 180 GHz.
4.2.3. Capillary Tube Architecture

Though the number of central holes was increased from one to nine, a considerable fraction of the beam is still subjected to material loss in the core, as shown in Fig. 4.3. A third proposed design incorporates capillary tubes to further decrease the material loss in the fiber core. A capillary is a thin dielectric wall filled with air. A holey core/cladding fiber using a bundle of square capillary tubes was designed. The design was optimized for mode confinement and loss improvements. The following describes the detailed optimization process.

First, a bundle of eight capillary tubes was stacked to create a holey core structure, as shown in Fig. 4.4.

The waveguide shown in Fig. 4.4, is a photonic crystal guiding a beam based on the antiresonant reflecting (ARR) mechanism [65]. Here, each wall of the capillary tube acts as a dielectric slab waveguide. At 360 GHz the beam is confined to the dielectric slab waveguides. Thus, there is no beam in the core of the structure. However, at lower frequencies (180 GHz), the beam can not propagate in the capillary walls. This results in leakage. The 180 GHz beam in the core of Fig. 4.4(c), (d) is due to the constructive interference of the leaky beams of the capillary walls. This design is narrow-band and core-confined propagation at higher frequencies (e.g. 360 GHz) is impossible.
Figure 4.4. Modes of a holey cladding capillary structure for horizontal and vertical polarizations. at (a), (b) 360 GHz. (c), (d) 180 GHz.

To increase beam confinement, another capillary tube was added to the core. This increased the number of dielectric slab waveguides and hence, the leaky modes. Fig. 4.5 shows a designed structure with one central capillary tube. A comparison between Fig. 4.4
and Fig. 4.5 shows the mode is more confined when the number of central capillary tubes is increased.

Figure 4.5. Simulations of a central capillary design at (a) 180 GHz and (b) 360 GHz demonstrates better mode confinement compared to the design shown in Fig. 4.4.

The number of central capillary tubes is increased to four, nine, and sixteen as shown in Fig. 4.6. The cladding capillary sizes and core capillary wall thicknesses are the same for all three designs. Eight square capillary tubes with 500 µm inner and 600 µm outer dimensions form the cladding. All central capillaries have a 25 µm wall thickness. Increasing the number of central hole capillary tubes increased the mode confinement. It is important to choose thin capillary walls to increase leakage and improve the mode confinement.
Figure 4.6. A mode confinement comparison between four, nine, and sixteen central hole capillary tubes at 180 GHz and 360 GHz. A four central capillary design at (a) 180 GHz and (b) 360 GHz. A nine central capillary design at (c) 180 GHz and (d) 360 GHz. A sixteen central capillary design at (e) 180 GHz and (f) 360 GHz.
Though adding more capillary tubes increases the beam confinement and operating bandwidth, it also increases the fiber loss. This could be studied with respect to the average refractive index of the core at different distances from the center.

Fig. 4.7 shows the average refractive index of the core as a function of \( s \) (half width of the square contours introduced in section 2.3.2) for a single, four, nine, and sixteen central hole design. The average refractive index of the core is 1.08, 1.22, 1.23, and 1.3 for single, four, nine, and sixteen central holes, respectively. This is due to higher material density in the core that results in a higher loss. Alternatively, adding more capillary tubes increases the probability of the leaky mode coupling from one capillary wall into another. This contributes to more loss since the beam travels in a dielectric rather than air.

Higher mode confinement increases as the number of central capillaries increases. This is due to the created higher refractive index walls. For example, in the nine central hole design, an array of refractive index walls at \( \sim 125 \, \mu \text{m} \) and \( 300 \, \mu \text{m} \) are tightly spaced. This provides for better beam confinement than the four central hole design. Note that some of the beam leaks out of the higher refractive index walls due to tunneling.
Figure 4.7. Averaged refractive index as a function of $s$ (half width of the square contours introduced in section 2.3.2) for single, four, nine, and sixteen central capillary structures.
Table 4.4 shows that the fiber loss and bandwidth increase as the number of the central capillary tubes increases.

Table 4.4. The loss comparison of three designs with different number of central capillaries.

<table>
<thead>
<tr>
<th>No. Capillary</th>
<th>Loss (180 GHz)</th>
<th>Loss (360 GHz)</th>
<th>Bandwidth</th>
<th>Confinement</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-central hole</td>
<td>0.03 [dB/cm]</td>
<td>0.11 [dB/cm]</td>
<td>195 GHz</td>
<td>Good</td>
</tr>
<tr>
<td>9-central hole</td>
<td>0.04 [dB/cm]</td>
<td>0.13 [dB/cm]</td>
<td>320 GHz</td>
<td>Better</td>
</tr>
<tr>
<td>16-central hole</td>
<td>0.05 [dB/cm]</td>
<td>0.15 [dB/cm]</td>
<td>420 GHz</td>
<td>Best</td>
</tr>
</tbody>
</table>

A design might be preferred depending on the application and preferences such as broadband transmission, low loss, isolation, and ease of fabrication.

Here, the design shown in Fig. 4.6 (a), (b) was chosen. The 1800 $\mu$m × 1800 $\mu$m waveguide consists of eight square capillary tubes with 500 $\mu$m inner, and 600 $\mu$m outer dimensions forming the cladding. Four square capillary tubes with 250 $\mu$m inner and 300 $\mu$m outer dimensions form the waveguide core. A factor of three loss improvement compared to the initial design (shown in Fig. 2.3) was calculated and shown in Table 4.5.

Table 4.5. Fiber loss comparison between the original design discussed in Chapter 2 to the third proposed design.

<table>
<thead>
<tr>
<th>Loss comparison</th>
<th>Original design</th>
<th>Proposed design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated loss (270 GHz)</td>
<td>0.22 [dB/cm]</td>
<td>0.07 [dB/cm]</td>
</tr>
</tbody>
</table>

In addition to loss improvement, square capillary tubes benefit from high packing density and easy assembly. A large variety of square capillary tubes are commercially available and may be used to assemble the structure. However, fabrication of capillaries with a 25 $\mu$m wall thickness requires advanced fabrication techniques that require development. Capillary structures based on the market size availability were simulated in the following.

As an example, Fig. 4.8 shows a design based on available square capillary tubes (from Wale Apparatus glass company). The number of central capillary tubes were changed to fit in
the center of the structure. A 2.52 mm $\times$ 2.52 mm capillary structure made of eight cladding capillaries with 840 $\mu$m and 600 $\mu$m outer and inner dimensions and sixteen central capillary with 200 $\mu$m and 150 $\mu$m outer and inner dimensions. This design shows an improvement factor of 1.3 compared to the original design discussed in Chapter 2.

Figure 4.8. A 2.52 mm $\times$ 2.52 mm capillary structure made of eight cladding capillary tubes (840 $\mu$m and 600 $\mu$m outer dimensions) and sixteen central capillary tubes (200 $\mu$m and 150 $\mu$m outer and inner dimensions).

To increase the mode confinement of this structure, the four capillary tubes in the corners of the cladding were removed, as shown in Fig. 4.9.
As a result, a low loss and broadband square capillary structure was created for PDM applications by creating a system of leaky waveguide channels. By controlling the core/cladding capillary (dielectric slab waveguide) number and sizes, new boundary conditions are created that force the beam to propagate in the air holes. This results in a broadband low loss transmission. The capillary tube design has lower loss compared to a solid core fiber and is broadband compared to a hollow core fiber.

The combination of a low loss geometry and low material loss has been shown to provide a $\sim 2$ dB to 15 dB loss for 1 m length of fiber. The loss is noticeably low compared to the original square solid core-holey cladding design discussed in Chapter 2, which showed a $\sim 24$ dB/m loss.
Two square dielectric waveguides with holey cladding were designed, fabricated and characterized for chip-to-chip PDM and SDM applications. The holey cladding was shown to be result from a straight-forward fabrication technique while maintaining a low fiber loss as confirmed by loss measurements. The simple design of a square waveguide geometry allows for polarization division multiplexing with minimum cross talk and polarization maintaining properties. A 2 mm × 2 mm waveguide with eight 400 μm diameter holes in the cladding was designed. Simulations demonstrated a broadband transmission across the frequency range of 180 GHz to 360 GHz.

The fiber loss simulations show 0.25 dB/cm at 300 GHz waveguide loss (TOPAS material loss is ~0.23 dB/cm at 300 GHz). This shows the designed geometry does not introduce more losses to the fiber. The bending loss studies showed that the fiber is resistant to bending loss, specially at higher frequencies. For a small bending radius of 10 mm (comparable to the 2 mm waveguide width) the loss is only 3 dB/m at 300 GHz. The fiber is more sensitive to bending at lower frequencies, since the beam is not perfectly confined to the core. This is one of the consequences of broadband transmission. The fiber core size was reduced to achieve a single mode fiber for a portion of the frequency range of interest (single mode from 180 GHz to 220 GHz) as the single mode across the whole bandwidth was not possible. Mode isolation and bending loss were shown to become an issue as the fiber size was reduced to support single mode. The averaged refractive index of the square waveguide was calculated using square contours to match the square geometry of the waveguide. The effective refractive index of the waveguide was simulated for both states of polarization across the frequency range of 180 GHz to 360 GHz. The effective refractive index was shown to increase with frequency. At higher frequencies the beam is mostly confined to the core, which has a higher
average index than the cladding as calculated.

A holey fiber was fabricated using the straight-forward drill and draw technique. The fabrication was done using a custom-built fiber drawing tower. The draw tower was designed to preserve the square geometry of the waveguide. Each step of the fabrication process was fine-tuned and controlled to achieve desired waveguide dimensions. Some fabrication defects were observed. Fabricated fiber geometries, including imperfections, were simulated. The simulations demonstrated good mode confinement to the core despite manufacturing defects.

Successfully fabricated fibers were characterized using a vector network analyzer with a pair of frequency extenders as source and detector operating in the frequency range of 220 GHz to 320 GHz. The mapped output mode profile of the waveguide, showing the mode is confined to the core, was in good agreement with the simulation. The fiber loss was measured using the same VNA setup. An asymmetric coupling component was used to increase the beam coupling efficiency into and out of the fiber. Characterization results showed an average 0.26 dB/cm fiber loss at 300 GHz, while the simulated system showed an average 0.25 dB/cm fiber loss). Fabricated fibers show higher loss that is attributed to fabrication imperfections.

A vortex THz fiber was designed, fabricated and, for the first time, experimentally characterized for SDM applications. The vortex waveguide simulation showed a successful transmission of the first two orders of an OAM endowed beam at 280 GHz. The amplitude of the output electric field shows good mode confinement. The phase plots of the output electric field (Fig. 3.3, 3.5) shows the phase is well-preserved throughout the transmission, though at higher order OAM the beam was slightly deformed near the cladding. The power loss and effective index were simulated for different waveguide sizes and different helicity orders, \( \ell \). The loss was shown to be higher as the order of \( \ell \) increased. For a fixed \( \ell \), the power loss decreases as the waveguide size increases. This is due to leakage of the beam with smaller waveguide sizes. The effective index decreases as the order of the mode increases since the outer radius of the beam travels through air holes.
The designed vortex THz fiber was fabricated using the same custom-built drawing tower. Successful transmission of the first order OAM beam by a fabricated vortex fiber at 280 GHz was shown experimentally. The first order OAM beam was generated using a plane wave generated by a VNA passed through a fabricated stepped spiral phase plate. The OAM characteristic of the transmitted beam through a vortex fiber was verified by a second, vertically inverted, discrete step spiral phase plate.

The experience gained in vortex fiber design inspired some low loss designs for PDM applications. The goal was to force the beam to travel in a holey core using the proper boundary condition provided by a holey cladding. A holey core provides a low loss transmission. Three designs were studied: a single hole core, a nine hole core, a four square capillary core. The designs were shown to provide broad-band transmission for low loss polarization division multiplexing. The square capillary tube structure outperformed the other designs since it provided the lowest loss (3 × loss improvement compared to the original solid core square waveguide). Additionally, the square geometry of the capillary tubes benefit tight packing density and easy assembly. A combination of low loss geometry and low material loss, as discussed, may be used to achieve an average of seven times loss improvement.
Appendix A
DETAILS OF THE RSOFT SIMULATIONS

The purpose of this appendix is to instruct a future researcher how to replicate the numerical design performed in this study.

The BeamProp simulation package was used to design the waveguides. BeamProp is fully integrated into the RSoft CAD environment that allows the user to define the geometry and material property of a component. Each simulation consists of three steps: structural design, launching condition definition and propagation simulation.

A.1. Square Holey THz Waveguide Simulations

A.1.1. Structure Design

The structural geometry was designed in the CAD environment of the RSoft package. A 2 mm × 2 mm × 1 m waveguide with eight 400 μm holes was plotted in the RSoft CAD layout (Fig. A.1) using the “segment” button on the left side toolbar. The geometric property of each segment can be defined using ”properties for segment” by right clicking on each segment in the drawing window. Fig. A.2 shows the segment properties of the square drawn in Fig. A.1. Fig. A.3 shows the segment properties of the circular holes.
Material properties, including the real and imaginary refractive indices, of each segment can be defined using the "Material Properties" drop-down menu in the "Properties for Segment" window. Material properties of some dielectrics are predefined in the material library of the software but TOPAS had to be added manually. TOPAS refractive index \( n = 1.5258 \) was added to the library using the "Edit Materials" option on left side toolbar (Fig. A.1). The refractive index of the holes are defined to be air \( (n = 1) \). It is very important to choose a higher merge priority for air holes compared to the square to create the correct
refractive index at each point. The "Merge Priority" option may be set in "properties for segment/Merge Priority" (Figs. A.3-A.2).

Figure A.2. Property control window showing property settings for the square segment of the waveguide filled with TOPAS. The structural geometry and material property may be set using this option.
Figure A.3. Property control window showing the property settings for the cladding air holes of the waveguide. The structure geometry and material property may be set using this option.

A plot of refractive index is simulated and shown in Fig. A.4 to make sure the refractive indices are correct. This is plotted using the "Display Material Profile" button on the left toolbar of the CAD window (Fig. A.1)

A.1.2. Launching Conditions

The launching conditions can be defined using the "Edit launch field" button on the left side toolbar of the CAD window (Fig. A.1). The waveguide mode profile depends on the waveguide geometry and refractive index and is independent of the launching condition.
Figure A.4. Refractive indices of all components. The waveguide cross section shows a square waveguide made with TOPAS ($n = 1.5258$). Eight holes form the cladding ($n = 1$).
Any launched beam could be used to simulate the mode of the waveguide. Here, a Gaussian beam was launched into the fiber. The mode calculation algorithm used in BeamProp was detailed in section 2.3. Fig. A.5 shows the launch field control settings. For this example a $1000 \mu m \times 1000 \mu m$ Gaussian beam was launched into the fiber. The launch field can be viewed using "view launch" button. Figure A.6 shows the Gaussian beam at the input of the fiber.

![Launch Parameters](image)

Figure A.5. The "Launching Parameters" setting window at the input of the fiber. A $1000 \mu m \times 1000 \mu m$ Gaussian wave is defined to feed into the waveguide.
The free space wavelength is set using the ”Edit Global Setting” button on the left hand side toolbar of the CAD layout window (Fig. A.1). For this example, the free space wavelength was chosen to be 833 µm for a 360 GHz wave.

A.1.3. Simulation

The fundamental waveguide mode profile was simulated using the ”Compute Modes” tool on the left hand side of the CAD layout window (Fig. A.1). The simulation parameters can be set in the ”Mode Calculation Parameters” window (Fig. A.7). The simulation domain was chosen large enough to consider the effect of the air surrounding the fiber. The polarization states can be chosen to be either TE or TM. The number of calculated modes
can be defined using the "Mode Option" button of the "Mode Calculation Parameter" window. The simulation starts with a large grid size to find the best geometry. Later, for more accurate simulations, the grid size is decreased until a stable result is achieved. The starting grid size in the square waveguide design was 10% of the smallest feature, which was the ∼300 µm between the holes. Once the design was roughly defined, the grid size was reduced to achieve stable results. A simulated effective index with an error smaller than 10^{-5} was a good indicator of a stable result. The error range was determined using the known TOPAS refractive index accuracy (1.5258). There is a limit on how small the grid size could be. A very small grid size results in unwanted reflections at the boundaries, that should be avoided. Figure A.7 shows the settings used to compute the fundamental mode of the waveguide.
Figure A.7. The "Mode Calculation Parameters" window. Simulation conditions such as grid size and state of polarization can be set here. The number of calculated modes may be set using "Mode Options" button.

The mode profile at the output of the fiber for an x-polarized 360 GHz launched beam is shown in Figure A.8.
Figure A.8. A fundamental waveguide mode simulated at 360 GHz.

The linear scale shows the magnitude of the electric field at each point. The effective refractive index is calculated and shown on top of the simulation window. The notation "m=0" indicates that the mode is calculated for the fundamental mode.

A.1.4. Fiber Loss Simulation

To measure the power loss at the output of the fiber a pathway monitor must be defined. A new pathway can be defined using the "Pathways" button on the left hand toolbar of the CAD window (Fig. A.1). For this example, the fiber length was chosen as the pathway as highlighted in green in Fig. A.9.
Figure A.9. Simulation pathway highlighted in green shows the waveguide length is chosen for simulation.

As shown in Fig. A.9, a monitor can be chosen for loss measurement using the "Monitors" option on the left side toolbar. A monitor for total power measurement, normalized to the input power, was chosen.

To consider material loss in the simulation an imaginary refractive index must be added to the material properties of TOPAS. This can be set using the "Edit Materials" option discussed in section A.1.1. The imaginary refractive index of TOPAS was calculated using the bulk material loss [28] and the following equation in the RSoft BeamProp (v2017.03)
where $n_{\text{imag}}$ is the imaginary refractive index, $\gamma$ is the material loss of TOPAS, and $\lambda$ is the wavelength.

Loss simulations are computed using the ”Perform Simulation” button on the right hand side of the CAD window (Fig. A.1). A simulated fiber loss measurements is shown in Fig. A.10. The normalized total power loss was calculated along the length of the fiber. For loss measurement the best launching condition must be defined to avoid any coupling loss effects. This could be done by looking at the output power while sweeping through several launch types and sizes.
Figure A.10. A simulated loss measurement example. A normalized power at each point along the fiber length is simulated.

A.2. Vortex THz waveguide simulations

A.2.1. Structure Design

First the structure was defined in the CAD environment. The structure design steps are detailed in section A.1.1.
A.2.2. Launching Conditions

OAM-endowed beams are not predefined in RSoft. An OAM beam was simulated using a set of patch antennas with phase shifts in the azimuthal direction. These settings can be done using the launching conditions detailed in section A.5. An example of a second order ($\ell = 2$) beam generation is shown in Fig. A.11.

![Second order OAM beam generation](image)

Figure A.11. A second order OAM beam generation. Sixteen patch antennas (orange squares) radiating with the same frequency and variable phase are set to generate an OAM beam. Their phases are set to create a $4\pi$ phase shift in one complete azimuthal rotation to create a second order ($\ell = 2$) OAM beam.

Fig. A.12 shows the phase information of the simulated second order OAM beam (Fig. A.11) at the input of a designed vortex fiber.
A.2.3. Simulation

The generated OAM (Fig. A.11) was launched into the vortex fiber. To simulate the beam profile at the output of the fiber the "Compute Modes" option (Fig. A.1) was selected. Detailed simulation settings are discussed in section A.1.3.

The output electric field is shown in Fig. A.13. Fig. 3.5 (a) shows that the mode is well-confined to the core. Fig. 3.5 (b) shows a $2\pi$ phase shift in the x-y plane.
Figure A.13. A FDTD convergence study of a fiber at 280 GHz. A 400 μm diameter center hole and 1100 μm (corners) and 800 μm (sides) cladding holes are outlined with circles. A second order OAM beam was launched into the fiber. (a) Magnitude and (b) phase of the electric field demonstrate that the designed fiber supports an ℓ=2 OAM beam.
Appendix B

DETAILED FIBER CHARACTERIZATION MEASUREMENTS AND CALCULATIONS

The purpose of this appendix is to instruct a future researcher how to replicate the measurement procedure and data analysis.

B.1. Vector Network Analyzer Basics

A vector network analyzer (VNA) measures the distortion of a component on a signal amplitude and phase. A VNA uses incident, reflected and transmitted waves that travel in a transmission line. Using optical wavelengths as an analogy, when light strikes a sheet of glass, some of the light is reflected back and some of it is transmitted through the glass. Using reflected, transmitted, and incident light on a glass sheet, its characteristics are defined. A VNA has two ports and measures four (two at each port) scattering parameters, called S-parameters, as shown in Fig. B.1. \( S_{11} \) and \( S_{22} \) are the reflected signal voltage to the incident at ports 1 and 2, respectively. \( S_{12} \) is the signal voltage transmitted from port 2 to port 1 to the incident. \( S_{12} \) is the signal voltage transmitted from port 1 to port 2 to the incident signal. S-parameters are complex numbers. This is used to get both the amplitude and phase of a reflected or transmitted wave.
Figure B.1. A VNA characterizes a sample by measuring the reflection and transmission signal voltages of an incident signal.

The VNA used for these experiments (Fig. B.2) was Agilent E8361C with the operating frequency of 10 MHz to 67 GHz. A pair of frequency extenders (OML V03VNA2-T/R) are used to perform measurements in the range of 220 GHz to 325 GHz.
Figure B.2. Experimental setup consists of a VNA (Agilent E8361C) along with two frequency extenders (OML V03VNA2-T/R) at the transmitter and receiver ends. The VNA and extenders provide a source and detector for radiation from 220 GHz to 325 GHz.

B.2. Calibration

A proper calibration kit needed to calibrate the setup was not available. The setup was calibrated only for transmission, $S_{21}$, as follows. The transmitter and receiver modules were connected using a WR0-2.8 straight waveguide as shown in Fig. B.3. From calibration settings in the VNA the setup was calibrated to yield a $\sim0$ dB transmission.
Figure B.3. Calibration setup. Receiver and transmitter modules are connected using a WR0-2.8 waveguide. The VNA is calibrated.

Fig. B.4 shows the transmission and reflection of the setup across the frequency range of 220 GHz to 320 GHz, with the WR0-2.8 waveguide connecting the two modules as shown in Fig. B.3. Full transmission (∼ 0 dB) is shown as expected, since the setup was calibrated for transmission.
Figure B.4. Measured S-parameters of the setup after calibration. S-parameters are measured when two modules are connected with WR0-2.8. As expected, a full transmission signal ($S_{12} \sim 0 \text{ dB}$) is measured. Reflection does not show the actual value since the VNA is not calibrated for reflection.

After calibration, fiber F150611c was used for characterization. Physical characteristics of the fiber are specified in Table 2.3. The reflections and transmissions were measured and compared as shown in Fig. B.5 for two cases. First, the fiber F150611c was mounted and properly aligned between the two modules. Then, the fiber was removed while keeping everything else the same. As shown in Fig. B.5, a 50 dB enhancement in transmission was observed. This showed that the waveguide increased the beam directivity.
Figure B.5. Reflection and transmission measurement comparison between a tested fiber and background. 50 dB transmission enhancement is measured compared to the background. This shows the fiber has increased the beam directivity.
B.3. Mode Mapping Setup and Measurements

The output mode profile of a waveguide was mapped using a profilometer setup. The transmitter module was placed on a z-stage and the receiver was placed on a stepped x-y stage to map the cross section of the waveguide in an x-y array. A 250 µm pinhole covered the aperture of the receiver. The pinhole was handmade as described here. A T-shaped aluminum sheet was cut out using a utility blade. A soda can was used due to the firmness of the material that makes the alignment of the pinhole easier. The dimensions of the T-shaped aluminum sheet was precisely measured using a caliper to ensure precise alignment on the press-fit pins of the receiver aperture as shown in Fig. B.6(c). The position of the hole was marked on the T-shaped aluminum sheet. A hole was pierced on the marked position. Fig. B.6(b) shows the pinhole under a microscope. The T-shaped aluminum sheet was precisely aligned on the receiver aperture. A 30 cm fiber was placed between the two modules on an x-y-z stage for proper alignment. The fiber output was then mapped in 250 µm steps.
Figure B.6. (a) A 250 µm pinhole was pierced into a T-shaped aluminum sheet. (b) Closeup picture of the pinhole under microscope. (c) Pinhole placed on the receiver aperture.

Data were saved as s2p text files that contain real and imaginary S-parameters. Fig. B.7 shows a sample s2p file of the measured real and imaginary S-parameters.
In each row of Fig. B.7, the first number is the frequency in units of Hz at which the measurement was done. The second and third numbers are the real and imaginary $S_{11}$ parameters. The fourth and fifth numbers are the real and imaginary $S_{21}$ parameters. The sixth and seventh numbers are the real and imaginary $S_{12}$ parameters. The eighth and ninth values are the real and imaginary $S_{22}$ parameters.

The magnitude of $S_{12}$ was calculated using

$$S_{12} = \sqrt{Re(S_{12})^2 + Im(S_{12})^2}. \quad (B.1)$$

An average $S_{12}$ is plotted in Fig. 2.26.
B.4. Fiber Loss Measurement and Calculations

The same setup with some alterations was used to measure the fiber loss. The VNA (Agilent E8361C), with a pair of frequency extenders (OML V03VNA2-T/R) used as a source and receiver, operates in the range of 220 GHz to 325 GHz.

To ensure efficient coupling into and out of the fiber, two components were used. A custom made taper with a 2 mm × 2 mm aperture was used to couple the beam from a WR-03 frequency extender aperture (0.86 mm × 0.43 mm aperture size) into the waveguide core (about 1 mm × 1 mm). The taper was fabricated by Mi-Wave Millimeter Products Inc. Fig. B.8 is the sketch of the taper dimensions provided by the company.

Figure B.8. Custom built taper sketch. (Provided by Mi-Wave Millimeter Inc)
To increase the coupling efficiency out of the fiber, a horn antenna with an aperture bigger than the waveguide dimension was used at the receiving end. A WR-03 horn with 25 dB gain and aperture size of 7.00 mm × 5.84 mm couples the wave out of the fiber efficiently while connected to the receiver.

The transmitter module was placed on a z-stage, the receiver module was placed on an (x-z)-stage, and the fiber under test (sample F150611c) was placed between the two modules. Each side of the fiber was placed on an (x-y-z)-stage for better alignment. The S-parameters of the fiber was measured in the best alignment condition. The frequency was set to 320 GHz to achieve the best alignment. Once the fiber is aligned at 320 GHz, it was found to also be aligned at lower frequencies. The (x-y-z)-stages of both ends of the fiber were aligned to maximize the $S_{12}$ (transmission).

S-parameter data was saved in an s2p format. The data was copied into an Excel file for analysis. Table B.1 shows the frequency and real and imaginary data for S-parameters.

Table B.1. An Excel file of exported S-parameters measured by the VNA.

<table>
<thead>
<tr>
<th>Freq [GHz]</th>
<th>Re $S_{11}$</th>
<th>Im $S_{11}$</th>
<th>Re $S_{21}$</th>
<th>Im $S_{21}$</th>
<th>Re $S_{12}$</th>
<th>Im $S_{12}$</th>
<th>Re $S_{22}$</th>
<th>Im $S_{22}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>-0.105</td>
<td>-0.068</td>
<td>-0.337</td>
<td>0.034</td>
<td>-0.345</td>
<td>-0.032</td>
<td>-0.090</td>
<td>-0.069</td>
</tr>
<tr>
<td>220.525</td>
<td>0.023</td>
<td>0.003</td>
<td>0.066</td>
<td>0.362</td>
<td>-0.159</td>
<td>-0.365</td>
<td>0.071</td>
<td>0.111</td>
</tr>
<tr>
<td>221.05</td>
<td>-0.008</td>
<td>-0.152</td>
<td>0.460</td>
<td>0.024</td>
<td>0.211</td>
<td>-0.282</td>
<td>-0.015</td>
<td>-0.188</td>
</tr>
<tr>
<td>221.575</td>
<td>-0.113</td>
<td>-0.099</td>
<td>0.149</td>
<td>-0.474</td>
<td>0.370</td>
<td>0.007</td>
<td>-0.139</td>
<td>0.034</td>
</tr>
<tr>
<td>222.1</td>
<td>0.051</td>
<td>0.101</td>
<td>-0.152</td>
<td>-0.319</td>
<td>0.208</td>
<td>0.337</td>
<td>0.063</td>
<td>-0.099</td>
</tr>
<tr>
<td>222.625</td>
<td>0.126</td>
<td>0.003</td>
<td>-0.254</td>
<td>-0.137</td>
<td>-0.203</td>
<td>0.316</td>
<td>-0.168</td>
<td>-0.070</td>
</tr>
</tbody>
</table>

The magnitude of S-parameters are calculated using $|S| = \sqrt{Re^2 + Im^2}$ as shown in Table B.2.
Table B.2. Calculated magnitude of the S-parameters.

<table>
<thead>
<tr>
<th>Freq [GHz]</th>
<th>Mag $S_{11}$</th>
<th>Mag $S_{21}$</th>
<th>Mag $S_{12}$</th>
<th>Mag $S_{22}$</th>
<th>$S_{11}$-Background</th>
<th>$S_{22}$-Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>0.125</td>
<td>0.339</td>
<td>0.347</td>
<td>0.114</td>
<td>0.061</td>
<td>0.046</td>
</tr>
<tr>
<td>220.525</td>
<td>0.024</td>
<td>0.367</td>
<td>0.398</td>
<td>0.132</td>
<td>0.083</td>
<td>0.093</td>
</tr>
<tr>
<td>221.05</td>
<td>0.152</td>
<td>0.460</td>
<td>0.353</td>
<td>0.189</td>
<td>0.015</td>
<td>0.151</td>
</tr>
<tr>
<td>221.575</td>
<td>0.150</td>
<td>0.497</td>
<td>0.370</td>
<td>0.143</td>
<td>0.041</td>
<td>0.061</td>
</tr>
<tr>
<td>222.1</td>
<td>0.113</td>
<td>0.354</td>
<td>0.396</td>
<td>0.117</td>
<td>0.007</td>
<td>0.043</td>
</tr>
<tr>
<td>222.625</td>
<td>0.126</td>
<td>0.289</td>
<td>0.376</td>
<td>0.182</td>
<td>0.108</td>
<td>0.142</td>
</tr>
</tbody>
</table>

Fiber loss is measured using

$$\text{Fiber Loss} = \frac{S_{12}}{C_1 C_2 T_1 T_2}. \tag{B.2}$$

The coupling inefficiencies are considered to be one since the taper and horn combination was used. Importantly, perfect coupling consideration means that the calculated fiber loss is higher than the actual fiber loss (Eq. B.2).

Table B.3 shows the calculated fiber loss in units of dB and dB/cm.

Table B.3. The calculated fiber loss for fiber F150611c.

<table>
<thead>
<tr>
<th>Freq [GHz]</th>
<th>Transmission1</th>
<th>Transmission2</th>
<th>Fiber Loss</th>
<th>Loss [dB]</th>
<th>Loss [dB/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>0.875</td>
<td>0.886</td>
<td>0.387</td>
<td>-8.246</td>
<td>-0.275</td>
</tr>
<tr>
<td>220.525</td>
<td>0.976</td>
<td>0.868</td>
<td>0.479</td>
<td>-6.398</td>
<td>-0.213</td>
</tr>
<tr>
<td>221.05</td>
<td>0.848</td>
<td>0.811</td>
<td>0.421</td>
<td>-7.506</td>
<td>-0.250</td>
</tr>
<tr>
<td>221.575</td>
<td>0.850</td>
<td>0.857</td>
<td>0.411</td>
<td>-7.727</td>
<td>-0.258</td>
</tr>
<tr>
<td>222.1</td>
<td>0.887</td>
<td>0.883</td>
<td>0.416</td>
<td>-7.613</td>
<td>-0.254</td>
</tr>
<tr>
<td>222.625</td>
<td>0.874</td>
<td>0.818</td>
<td>0.491</td>
<td>-6.178</td>
<td>-0.206</td>
</tr>
</tbody>
</table>

The calculated fiber loss across the frequency range of 220 GHz to 320 GHz is shown in Fig. 2.33.
Appendix C

FIBER FABRICATION TRAVELER

Each step of fiber fabrication was documented and fine-tuned to achieve the desired fibers. The following is the updated traveler used to document the fabrication process.
TRAVELLER

TOPAS Holey Fiber Preparation and Characterization

<table>
<thead>
<tr>
<th>Date</th>
<th>Process</th>
<th>Procedure/Parameters</th>
<th># IN</th>
<th># OUT</th>
<th>Oper</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Preform Making Preparation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clean spray residue and TOPAS residue from mold walls</td>
<td>Use small brush to clean the spray residue and use razor blade to get rid of the TOPAS residue. (downstairs loading dock)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spray all the molds</td>
<td>All the upright walls need be slightly sprayed (spray time 1 second), and the bottom walls need to be heavily sprayed (spray time 3 seconds). The distance between spray and the object should be between 0.5m-0.8m. Let the molds stay for more than 5 minutes after the spray. (wear glove, downstairs loading dock)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mold assemble</td>
<td>Assemble 3 molds; the aluminum mold requires one long screw on the upper right screw hole.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Molds setup</td>
<td>Set all three assembled molds onto hot plate. And put a metal plate between the hot plate and molds.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Preform Making Procedure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Preheat</td>
<td>Set the hot plate to 2 blocks above 200 (T2) on the analog temperature dial, and then cover it with a black box. Wait 1 hour 30 minutes.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Add layers</td>
<td>Add each layer less than 20 ml of TOPAS material (spread the TOPAS material homogenously on the surface), each layer takes 40 minutes to melt. Turn up the temperature to T3 at the 6th layer.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Last layer and soak</td>
<td>When it's the last layer, put the molds into the oven which already been preheated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
to its highest temperature 230°C for 40 minutes. Then let them cool down inside the oven overnight

<table>
<thead>
<tr>
<th>Procedure record</th>
<th>Preheat time _____, temperature _____</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1&lt;sup&gt;st&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
<tr>
<td></td>
<td>4&lt;sup&gt;th&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
<tr>
<td></td>
<td>5&lt;sup&gt;th&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
<tr>
<td></td>
<td>6&lt;sup&gt;th&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
<tr>
<td></td>
<td>7&lt;sup&gt;th&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
<tr>
<td></td>
<td>8&lt;sup&gt;th&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
<tr>
<td></td>
<td>9&lt;sup&gt;th&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
<tr>
<td></td>
<td>10&lt;sup&gt;th&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
<tr>
<td></td>
<td>11&lt;sup&gt;th&lt;/sup&gt; layer time _____, temperature _____</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total layer</th>
<th>Total layers number ____________</th>
</tr>
</thead>
<tbody>
<tr>
<td>-------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>-------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Preform No._____, Preform hole drilling</td>
<td></td>
</tr>
<tr>
<td>----------------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Hole pattern</strong></td>
<td>Use pen to mark holes position on the flat side of the preform. Hole pattern structure:__________, Distance between center hole and the edge ________cm, Distance between side hole and the edge ________cm.</td>
</tr>
<tr>
<td><strong>Drill procedure</strong></td>
<td>Start drilling with the smaller size drill bits, then move to bigger size drill bits. Clean the residue on drill bits each time when it pulled up from the holes. Starting drill bit size:_______ Ending drill bit size:_______ Note: 1. Put little amount of water into the holes will help drilling. The material tends to stick less on the drill bits. 2. Drill into a short depth each time will also help the drill bits last longer and less likely stuck into the holes.</td>
</tr>
<tr>
<td><strong>Hole polish</strong></td>
<td>When the hole drilled through, turn on the drill and let it stay inside the hole for a while. This helps polish the inside of the holes.</td>
</tr>
<tr>
<td><strong>Mark screw position</strong></td>
<td>Put the drilled preform into the preform holder, make sure the preform is aligned well, then mark one side of the preform, tighten 4 screws on the preform holder to leave marks on the preform.</td>
</tr>
<tr>
<td><strong>Drill holder screw hole</strong></td>
<td>Release the preform from the preform holder, use 1/8 size drill bit to drill holes on the screw marks (this helps the holder screw hold preform better when it's heating in the oven).</td>
</tr>
<tr>
<td><strong>Preform position setup</strong></td>
<td>Put the mark size of the preform the same position when it's marked in the</td>
</tr>
<tr>
<td>Preform</td>
<td>Fiber</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>preform and use a double sided tape to hold the preform in preform holder better.</td>
<td></td>
</tr>
<tr>
<td>Double side type: Y / N.</td>
<td></td>
</tr>
<tr>
<td>And then put the preform holder on the stage, aligned it well, adjust the position of the preform:</td>
<td></td>
</tr>
<tr>
<td>______ cm to from inner oven sides,</td>
<td></td>
</tr>
<tr>
<td>______ cm from bottom of preform to bottom of oven</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fiber pulling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preheat</td>
</tr>
<tr>
<td>Preheat temperature: ______ °C (____ V on variac),</td>
</tr>
<tr>
<td>Projecting preheat time: ______ hours____ minutes.</td>
</tr>
<tr>
<td>Actual preheat time: ______ hours ______ minutes.</td>
</tr>
<tr>
<td>Thermocouple inside heating plate read (after the temperature is stable): ______ °C (________ mV)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pulling temperature</th>
<th>After preheat, turn on the temperature to pulling temperature.</th>
</tr>
</thead>
<tbody>
<tr>
<td>______ °C, (_______ V on variac)</td>
<td></td>
</tr>
<tr>
<td>When stable, thermocouple temperature ________ mV.</td>
<td></td>
</tr>
</tbody>
</table>

| Neck down | Time takes for necking down after turned up the temperature: ________ minutes. |
| **Stage feeder** | Set the stage to ____ Hz, move down rate: _____ mm/sec.  
| Use “+” bottom on the monitor to move down the stage. |

| **Fiber roller collector** | Fiber wheel 1 rotation takes time: ____ minutes ____ seconds.  
| = _______ rad/sec  
| = _______ mm/sec |

| **Pulling time** | Time pulling ends: _______  
| Process ending situation: _______ |

| **Fiber characterization** |
| Measure diameter | Using caliper to measure the diameter of the fibers every ____ cm, and measure both side.  
| Fiber total length: _______.  
| Excel document name: _______ |

| Select uniform fiber | Plot the diameter in excel sheet, choose the uniform part (variation less than 10%) and cut them. |

| Number fiber | Select and several uniform part of the fiber and cut them down, mark them:  
| _____a,  
| _____b  
| _____c  
| _____d  
| _____e  
| _______ |

| Cross section | Polish the side of the fibers and watch them under microscope, and take picture of the cross section.  
| Picture name:  
| One side _______. _______, the  
| other side _______. _______ for a,  
| One side _______. _______, the |
Preform______Fiber_______

| other side ______, ______ for b, |       |       |
| One side ______, ______, the    |       |       |
| other side ______, ______ for c, |       |       |
| One side ______, ______, the    |       |       |
| other side ______, ______ for d, |       |       |
| One side ______, ______, the    |       |       |
| other side ______, ______ for e. |       |       |
BIBLIOGRAPHY


