MODE VOLUME REDUCTION IN SINGLE CRYSTAL SAPPHIRE OPTICAL FIBERS

Yujie Cheng

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy
In
Materials Science and Engineering

Gary R Pickrell, Chair
Bill T Reynolds
Carlos T A Suchicital
Anbo Wang

02-16-2017

Blacksburg, Virginia

Keywords: single crystal sapphire, mode volume reduction
MODE VOLUME REDUCTION IN SINGLE CRYSTAL SAPPHIRE OPTICAL FIBERS

Yujie Cheng

(ABSTRACT)

This research provides the original work on the geometry factors selection for single crystal sapphire optical fiber (SCSF) to reduce the number of guided modes via a highly dispersive cladding with a periodic array of high- and low-index regions in the azimuthal direction. And the first design on a large-core single-mode “windmill” single crystal sapphire optical fiber (SCSF), including the first production of “windmill” single crystal sapphire optical fiber (SCSF) by the bundling method.

The theoretical modeling and numerical analysis described the optical behavior of modal volume reduction. The modal characteristics and confinement losses of the fundamental mode were analyzed via the finite element method by varying the effective core diameter and the dimensions of the “windmill”-shaped cladding.

Single crystal sapphire fibers were fabricated with a Laser Heated Pedestal Growth (LHPG) system, which was constructed in-house at Virginia Tech. The cost effective, high efficiency and fully operational Laser-heated Pedestal Growth (LHPG) system as well as the fiber fabrication process were also demonstrated in this research.

The demonstration of modal volume reduction in windmill single crystal sapphire optical fiber (SCSF) indicated the windmill single crystal sapphire optical fiber (SCSF) will readily improve
the performance of current fiber optic sensors in the harsh environment and potentially enable those that are limited by the extremely large modal volume of unclad single crystal sapphire optical fiber (SCSF).
MODE VOLUME REDUCTION IN SINGLE CRYSTAL SAPPHIRE OPTICAL FIBERS

Yujie Cheng

(GENERAL AUDIENCE ABSTRACT)

This research provides the original work on the geometry factors selection for single crystal sapphire optical fiber (SCSF) to improve the optical property in sensing applications. Single crystal sapphire fibers were fabricated with a Laser Heated Pedestal Growth (LHPG) system, which was constructed in-house at Virginia Tech. The cost effective, high efficiency and fully operational Laser-heated Pedestal Growth (LHPG) system as well as the fiber fabrication process were also demonstrated in this research. The results indicated the windmill single crystal sapphire optical fiber (SCSF) will readily improve the performance of current fiber optic sensors in the harsh environment and potentially enable those that are limited by the optical property of unclad single crystal sapphire optical fiber (SCSF).
ACKNOWLEDGEMENTS

I would like to acknowledge financial support for significant portions of this work from the National Energy Technology Lab (NETL) at the U.S. Department of Energy (DOE) under contract DE-FE0012274. I would also like to thank my advisor, Dr. Gary Pickrell, for his constant assistance, support, and advice as this work was planned and enacted. I am especially grateful to Dr. Pickrell’s patience and procurement of resources when I was initially learning the fundamentals of this field in which I had little prior knowledge or training. The initial concept of “windmill” shaped sapphire optical fiber (which was fundamental to this research) conceived by Dr. Gary Pickrell; I am grateful that he so freely discussed his initial findings with me and encouraged me to carry the work forward to its current state. Dr. Dan Homa provided key advice and training at numerous intervals in this research for which I am thankful in addition to his general mentorship. I also appreciate the advice, encouragement, and refining wisdom provided by my committee members: Dr. Bill Reynolds, Dr. Carlos Suchicitlal, and Dr. Anbo Wang.

Dr. Zhihao Yu, Dr. Haifeng Xuan and Bo Liu provided patient advice whenever I sought their wisdom, which was extremely valuable in guiding the numerical modeling on my “windmill” sapphire fiber. Dr. Haifeng Xuan provided crucial assistance in numerical modeling method in COMOSL and was always willing to give his time and expertise freely and expediently and with admirable selflessness. Several of my group-mates and fellow students have provided other support and assistance throughout this work, especially Adam Floyd and Dr. Cary Hill.
I’ll also thank all my friends in Blacksburg, many of whom were also my colleagues at both CPT and MSE. Specially, I would like to thank Shuo Yang, Di Hu, Zhipeng Tian, Edward Liang, Brian Scott, Gurbinder Kaur.

Personally, I thank my husband for his continued patience and support. My parents, they supported my study in the United State since 2009. Most of all, I thank the Lord Jesus for the life, skills, and brain given to me. I simply would not have even attempted to complete this degree with my husband and parents to support without full faith that I was merely following a path set before me.
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Theoretical Background</td>
<td>9</td>
</tr>
<tr>
<td>2.1</td>
<td>Mode volume reduction in Optical Fiber</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Confinement Loss and Perfect Matched Layer</td>
<td>16</td>
</tr>
<tr>
<td>2.3</td>
<td>Numerical Analysis</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>Fiber Design, Optimization and Analysis</td>
<td>19</td>
</tr>
<tr>
<td>3.1</td>
<td>“Windmill” single crystal sapphire optical fiber (SCSF)</td>
<td>21</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Mode volume reduction</td>
<td>23</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Confinement loss of the fundamental mode</td>
<td>25</td>
</tr>
<tr>
<td>3.1.3</td>
<td>Refractive index as a function of wavelength</td>
<td>26</td>
</tr>
<tr>
<td>3.2</td>
<td>Single mode optical fibers</td>
<td>28</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Optimized structure of single mode “windmill” single crystal sapphire optical fiber (SCSF) with large core size</td>
<td>29</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Single-mode operation</td>
<td>35</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Electric field distribution</td>
<td>40</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Confinement loss and refractive index as function of wavelength</td>
<td>41</td>
</tr>
<tr>
<td>3.3</td>
<td>Bundled “Windmill” single crystal sapphire optical fiber (SCSF)</td>
<td>46</td>
</tr>
<tr>
<td>4</td>
<td>Fiber Fabrication Experimental Procedures</td>
<td>61</td>
</tr>
<tr>
<td>4.1</td>
<td>Single crystal sapphire optical fiber (SCSF) Fabrication by Laser-heated Pedestal Growth (LHPG) System</td>
<td>61</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Laser-heated Pedestal Growth (LHPG) system</td>
<td>61</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Fiber pulling process in fiber growth chamber</td>
<td>68</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Mechanical pulling system and control</td>
<td>70</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Feed and Seed Preparation</td>
<td>72</td>
</tr>
<tr>
<td>4.1.5</td>
<td>Fiber Bundling</td>
<td>73</td>
</tr>
<tr>
<td>4.2</td>
<td>Optical Analysis</td>
<td>74</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Far-Field Projection Measurement</td>
<td>74</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Numerical Aperture Measurement</td>
<td>76</td>
</tr>
<tr>
<td>5</td>
<td>Numerical Modeling and Fabrication on the Bundled “Windmill” SCSF</td>
<td>79</td>
</tr>
<tr>
<td>5.1</td>
<td>Numerical Modeling on Electric Field Distribution</td>
<td>79</td>
</tr>
<tr>
<td>5.2</td>
<td>Fabrication</td>
<td>83</td>
</tr>
<tr>
<td>6</td>
<td>Conclusion</td>
<td>86</td>
</tr>
</tbody>
</table>
7. Future Work ................................................................. 88
Reference ........................................................................... 89
Appendices ........................................................................ 92
A. Function block in the Parker Linear stages control system........... 92
B. Global variables in the Parker Linear stages control system........... 94
C. Parker Linear Stages’ code .................................................. 95
List of Figures

Figure 1. TIR, acceptance angle and critical angle of an optical fiber. ................................. 10
Figure 2. The schematic of the cylindrical coordinate system in an optical fiber. Reprint from Fundamentals of Photonics, 2nd Edition (Figure 9.2-1), By Bahaa E. A. Saleh, Malvin Carl Teich, Wiley Books. Copyright (2007) by Wiley Books ......................... 11
Figure 4. Electric field amplitude profiles for part of the guided modes of a MMF [32]. Source: RP Photonics Consulting GmbH, generated with the RP Fiber Power software. ..... 15
Figure 5. Blackbody radiation curves [40]. Reprint from Thermal Infrared Remote Sensing: Theoretical Background of Thermal Infrared Remote Sensing (Figure 1.5), By Claudia Kuenzer, Springer. Copyright (2013) by Springer. ........................................... 20
Figure 6. Structure of SCSF with a “windmill” core (a); “windmill” fiber (d=5μm) with different a and b parameters (b); fundamental mode energy pattern in the E field “windmill” fiber with d=5μm, a=1.5μm, b=0.2μm (c) ............................................................ 22
Figure 7. “Windmill” SCSF (in Figure 6) in the simulation environment ............................... 22
Figure 8. Number of guided modes in conventional fiber with diminishing diameter (a); a “windmill” fiber with combination of a and b for 70 μm diameter (b); 50 μm diameter (c); 30 μm diameter (d); 10 μm diameter (e); 5 μm diameter (f). ............. 24
Figure 9. Refractive index for SCSF and “windmill” SCSF as a function of wavelength. Electric filed distribution for “windmill” SCSF at wavelength of 0.24μm and 2μm were inserted .......................................................... 27
Figure 10. “Windmill” SCSF design with different N parameter at fixed d, a and b parameters. 31
Figure 11. First mode in the “windmill” SCSF with N=4. ....................................................... 31
Figure 12. First three modes in the “windmill” SCSF with N=6 ............................................ 32
Figure 13. First four modes in the “windmill” SCSF with N=8 ............................................ 33
Figure 14. The fundamental mode (A) and the high order mode (B) in the “windmill” SCSF with N=20. .................................................................................. 33
Figure 15. Structure of “windmill” SCSF ........................................................................... 35
Figure 16. “Windmill” structure with a small semi-minor axis b (A) and a large semi-minor axis b (B). ......................................................................................................................... 36
Figure 17. “Windmill” structure with a small semi-major axis a (A) and a large semi-major axis a (B). .......................................................................................................................... 37
Figure 18. Variation of confinement loss of the FM (solid line) and higher-order mode (HOM) (dash line) as a function of the parameter a and b for a SCSF with diameter of (a) 70μm; (b) 50μm; (c) 30μm. The legend for example: FM_b2 means the fundamental mode at b=2μm. ................................................................. 39
Figure 19. Electric field contour plot of the optimized “windmill” SCSF on fundamental mode (FM) (top) and higher-order mode (HOM) (bottom) with diameter of (a) 70μm; (b) 50μm; (c) 30μm. ........................................................................ 40
Figure 20. “Windmill” SCSF with 30μm diameter (a) electric field distribution at a wavelength of 0.4μm; (b) electric field distribution at a wavelength of 2μm; (c) confinement loss as a function of wavelength; (d) refractive index as a function of wavelength. 43

Figure 21. “Windmill” SCSF with 50μm diameter (a) electric field distribution at a wavelength of 0.4μm; (b) electric field distribution at a wavelength of 2μm; (c) confinement loss as a function of wavelength; (d) refractive index as a function of wavelength. 44

Figure 22. “Windmill” SCSF with 70μm diameter (a) electric field distribution at a wavelength of 0.4μm; (b) electric field distribution at a wavelength of 2μm; (c) confinement loss as a function of wavelength; (d) refractive index as a function of wavelength. 45

Figure 23. Bundled “windmill” SCSF structure. 46

Figure 24. Four-layer bundled “windmill” SCSF in simulation environment with (A) 6-ring structure and (B) 12-ring structure. 47

Figure 25. Electric field distribution of fundamental mode (FM) of conventional SCSF with diameter of (A) 1.6μm (B) 1.4μm (C) 1.2μm (D) 1.0μm (E) 0.8μm (F) 0.6μm (G) 0.4μm. 48

Figure 26. Electric field distribution of fundamental mode (FM) of four-layer 6-ring “windmill” structure SCSF with the core diameter of (A) 1.6μm (B) 1.4μm (C) 1.2μm (D) 1.0μm (E) 0.8μm (F) 0.6μm (G) 0.4μm. 50

Figure 27. Electric field distribution of FM of 12-ring “windmill” structure SCSF with the core diameter of (A) 1.6μm (B) 1.4μm (C) 1.2μm (D) 1.0μm (E) 0.8μm (F) 0.6μm (G) 0.4μm. 51

Figure 28. Electric field distribution of higher-order mode (HOM) of 12-ring “windmill” structure SCSF with the core diameter of (A) 1.6μm (B) 1.4μm (C) 1.2μm (D) 1.0μm (E) 0.8μm (F) 0.6μm (G) 0.4μm. 52

Figure 29. Bundled “windmill” SFSC with (a) 4 layers; (b) 3 layers; (c) 2 layers; (d) 1 layer. 54

Figure 30. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 4 layers bundled “windmill” SCSF. 55

Figure 31. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 3 layers bundled “windmill” SCSF. 56

Figure 32. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 2 layers bundled “windmill” SCSF. 57

Figure 33. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 1 layer bundled “windmill” SCSF. 58

Figure 34. Confinement loss on the studied modes in bundled “windmill” SCSF. 60

Figure 35. Schematic drawing of the Laser-heated Pedestal Growth (LHPG) out of chamber design. 63

Figure 36. Beam Steering Optics of the LHPG system. 64

Figure 37. Schematic drawing of the LHPG in chamber design[48]. Reprint from Laser-Heated Pedestal Growth of Oxide Fibers (Figure13.2), by Marcello R.B. Andreeta, Springer. Copyright (2010) by Springer. 65

Figure 38. The (A) Upper and (B) Lower linear stage with manual linear stage and the fiber chuck. 66

Figure 39. (A) A Parabolic Mirror; (B) Reflexicon and Scraper Mirror. 67
Figure 40. Laser-heated Pedestal Growth (LHPG) system .......................................................... 68

Figure 41. Schematic drawing of the four steps performed in the Laser-heated Pedestal Growth (LHPG) technique: (I) mechanical alignment of the seed and the pedestal and (II) creation of a small molten zone on the top of the pedestal. (III) The seed was then introduced in the liquid phase and there was creation of a molten zone. (IV) The fiber-pulling process begins[48]. Reprint from Laser-Heated Pedestal Growth of Oxide Fibers (Figure 13.5), by Marcello R.B. Andreeta, Springer. Copyright (2010) by Springer .......................................................... 69

Figure 42. The Parker linear stage fiber pulling control Panel .................................................. 71

Figure 43. The Parker linear stage Setup Screen Panel ............................................................ 72

Figure 44. Single crystal sapphire fiber during growing process in LHPG growth chamber ...... 73

Figure 45. The fiber bundle has produced by a fiber funnel ....................................................... 74

Figure 46. Schematic drawing of the far-field projection measurement .................................... 76

Figure 47. Numerical aperture measurement and calculation .................................................... 78

Figure 48. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 1 layers bundled “windmill” SCSF with 325μm diameter at 532nm wavelength.......................................................... 80

Figure 49. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 1 layers bundled “windmill” SCSF with 325μm diameter at 780nm wavelength .......................................................... 81

Figure 50. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 1 layers bundled “windmill” SCSF with 325μm diameter at 980nm wavelength .......................................................... 82

Figure 51. Picture of as grown 115μm diameter sapphire fiber ............................................. 83

Figure 52. As grown sapphire fiber with diameter of 115μm under optical microscope .......... 83

Figure 53. 5X magnification of bundled “windmill” SCSF with a core diameter of 325μm ...... 84

Figure 54. 10X magnification of bundled “windmill” SCSF with a core diameter of 325μm .... 85

List of Tables

Table 1 Available coatings/claddings on single crystal sapphire fiber ...................................... 6

Table 2 Structure parameters and Confinement loss (CL) of the fundamental mode for “windmill” fibers in each group .......................................................... 25
1. Introduction

Optical fibers are widely used in communications and sensing systems due to the advantages over conventional electrical and acoustic temperature sensors, such as high sensitivity, compact size, immunity to EMI, etc. They are available from many materials such as glass, polymers and single crystals in a huge variety of dimensions and structures. Various ideas have been proposed and techniques have been developed for different applications [1]. To date, however, only some types of optical fiber sensors have been commercialized. And among the various techniques that have been studied, only a limited number of techniques and applications have been commercially successful. Harsh environments are often unavoidable in many industrial applications and one of the big challenges in industries, especially in power generation and nuclear power plants [2].

Sapphire has a very high melting temperature (approximately 2054ºC) and excellent chemical durability in highly corrosive environments [3, 4]. Single crystal sapphire ($\alpha$-Al$_2$O$_3$) is also a material of choice for optical components because of its wide transparency range (0.24-4μm) [5]. Silica fibers are frequently used for infrared spectroscopy and for temperature sensing in high temperature environment, however, silica fibers cannot be used for wavelength greater than about 2.3μm or for temperature greater than about 1200 ºC because of devitrification [6]. Therefore, compared with traditional silica based materials, single crystal sapphire is an ideal candidate for harsh environment fiber optic sensors above 1400ºC [4, 7, 8].

Extensive studies have been performed on sapphire sensor technology and some of which have now reached commercialization stages. In the ultrahigh temperature applications, Grobnic et al. [9] reported the inscription of retro-reflective Bragg gratings in multimode crystalline sapphire fiber as a temperature sensor. They also investigated the grating behavior up to 1500ºC and measured the change in the effective index of the fiber as a function of temperature.
al. [2] developed a single crystal sapphire based optical high temperature sensor for harsh environment. By employing a single-crystal sapphire disk and a fully stabilized zirconia right-angle prism, a prototype of an optical high-temperature measurement instrument for harsh environments was designed and tested. In their research, temperature information had a wide dynamic measurement range from room temperature up to 1600°C. Lee et al. [10] presented a sapphire fiber high temperature tip sensor with multilayer coating. The multilayer coated sapphire fiber was used as a Fabry-Perot interferometer and had a sensitivity of 40.7pm/°C when temperature was changed from 400°C to 1000°C. Wang et al. [11] also developed a sapphire fiber air gap based extrinsic Fabry-Perot interferometers, which has a temperature sensitivity above 20nm/ °C and a resolution less than 0.3 °C above 1000 °C. Not only in the temperature sensing but also in the pressure sensing at high temperature there has been a focus on the use of sapphire as the sensor material. Mills et al. [12] demonstrated the sapphire micro machined wall shear stress sensor for high temperature applications utilizing geometric moiré optical transduction. It was reported that the shear stress sensitivity, based on the designed sensor, was 76.8µV/Pa at 1.128 kHz.

However, to date, unclad single crystal sapphire fibers (SCSFs) are highly multimodal due to fabrication limitations resulting in large diameters and high numerical apertures. Without a physical cladding, the whole volume of the single crystal sapphire optical fiber (SCSF) was considered to be the core, and the surrounding air the cladding. The commercially available SCSFs usually have diameters between 100μm to 300μm [13]. In Fabry-Perot sensor applications, interference signals were degraded by the multimode electromagnetic fields in multimode sapphire fibers [2, 14]. Furthermore, the large number of modes present in single crystal sapphire optical fiber (SCSF) preclude the use of distributed sensing technologies such as
Brillouin and Raman scattering based sensors due, in part, to modal dispersion [15]. Generally, the extremely large number of modes that propagate in this waveguide structure degrades the accuracy, resolution, and ultimate performance of the chosen sensing systems.

Several single crystal sapphire optical fiber (SCSF) designs have been explored to improve the mechanical reliability and optical properties. Coatings can isolate the fiber from environmental contaminants and protect the surface from mechanical abrasion. Besides, coating the sapphire fiber to generate a cladding will enable wider use of sapphire fiber by improving the optical properties. However, there is no single candidate material that can serve as a sapphire fiber cladding in any environment; the cladding should be chosen depending to its application [16]. The use of cladding materials such as Teflon [17] and alumina [18], as well as others, have been shown to reduce the number of guided modes. However, both Teflon cladding applied by melt extruder and alumina cladding applied via a sol-gel approach inevitably increase the transmission loss. In recent years, several research groups attempted to develop sapphire cladding using refractory materials such as polycrystalline alumina (Al₂O₃), metal niobium, silicon carbide (SiC), and zirconia (ZrO₂) [13]. These materials have major issues of chemical or structural instabilities at high temperatures. Due to the identical chemical composition, polycrystalline alumina can readily incorporate into the sapphire phase that causes the cladding/core interface to disappear [19]. The silicon carbide and metal cladding layers readily react in the high temperature oxidizing atmospheres [19]. The zirconia cladding layer is generally ineffective for improving the waveguide efficiency because it has a refractive index greater than sapphire; also zirconia experiences a monoclinic-to-tetragonal phase transition at around 1000°C leading to a large volume change which can induce structural damage in the cladding and/or the fiber’s core [20]. Niobium seems be to an attractive candidate for sapphire
cladding due to its low CTE mismatch to sapphire. It has great resistance with sodium, mercury and other chemical substances at elevated temperature, however, a high sodium vapor atmosphere at over 1000°C will trigger a reaction between the niobium and alumina [19]. Jiang et al. [21] also presented a spinel MgAl₂O₃ thin film coating with 800nm thickness on single crystal sapphire fibers and wafers for high temperature applications. This spinel-cladded sapphire fiber was chemically stable up to 1200°C. However, the spinel became thermodynamically unstable when temperature exceed 1250 °C. Table 1 compares the maximum working temperature, advantages and disadvantages of different coatings/claddings materials that have been investigated on single crystal sapphire fiber.

In addition, confining light propagation within the sapphire fiber remains difficult in practice due to mechanical and/or chemical failure of the cladding materials under extremely high temperatures [13]. Even if a cladding layer applied on the fiber surface survives in harsh conditions, adding a cladding by any coating technique does not reduce the core diameter and the core diameter cannot be reduced below a few tens of micrometers during fabrication process. Many modes remain in the sapphire fibers due to the large core size and relatively large refractive index delta. Recently, another method to obtain a more traditional core-cladding structure in single crystal sapphire optical fiber (SCSF) was attempted via the formation of nanometer sized cavities in the sapphire by hydrogen ion implantation [22]. The nanometer scale cavities create a slightly smaller refractive index compared with sapphire, and therefore, have been proposed as a potential sapphire fiber cladding. However, the size and distribution of these nano-cavities was very difficult to control and modify. Also, the refractive index changed during a high a temperature annealing process and an unstable refractive index profile will significantly
degrade the performance of the optical fiber sensors that rely on the use of the single crystal sapphire optical fiber (SCSF).
<table>
<thead>
<tr>
<th>Cladding materials</th>
<th>Maximum temperature</th>
<th>Advantages / Benefits</th>
<th>Disadvantages / Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teflon [17]</td>
<td>200°C</td>
<td>Does not alter the loss of the fiber</td>
<td>Cannot be used above 200°C</td>
</tr>
<tr>
<td>Alumina (Al$_2$O$_3$) [17, 18]</td>
<td>1600°C</td>
<td>Provide high-temperature clad</td>
<td>Hard to remove water from coatings; time consuming; difficult to build a thicker layer</td>
</tr>
<tr>
<td>Silicon carbide (SiC) [19]</td>
<td>1400°C</td>
<td>Strong, dense and thermally shock resistant</td>
<td>Oxidized above 1400°C; best used in a reducing atmosphere</td>
</tr>
<tr>
<td>Zirconia (ZrO$_2$) [20]</td>
<td>1000°C</td>
<td>Stable in both oxidizing and moderately reducing atmosphere</td>
<td>Refractive index greater than sapphire; phase transition around 1000°C cause damage to fiber</td>
</tr>
<tr>
<td>Niobium [19]</td>
<td>1000°C</td>
<td>Low CTE mismatch to sapphire</td>
<td>Reacts with alumina above 1000°C</td>
</tr>
<tr>
<td>Spinel (MgAl$_2$O$_3$) [21]</td>
<td>1200°C</td>
<td>Chemically stable up to 1200°C</td>
<td>Thermodynamically unstable when temperature exceeds 1250 ºC</td>
</tr>
</tbody>
</table>
Despite the highly multimode property, the power loss associated with design of the core is another challenge in sensing applications. The decrease of the fiber’s diameter and/or Numerical Aperture (NA), as well as the addition of voids in the cladding, may reduce the number of modes confined in the core. Confinement loss (CL) describes the ability of the core to confine the light, which is also known as confinement capability, due to a finite number of holes, and can be estimated in a fiber [23, 24]. A finite periodic cladding causes a decrease in optical confinement resulting in a loss increase that is referred to as the confinement loss [25]. Single crystal sapphire optical fiber (SCSF) with a low mode volume and high confinement capability is preferred in sensor applications, and can be achieved by a proper fiber structure design.

The fiber structure designed in this research was similar to the “segmented-cladding” silica fiber design previously explored for application in fused silica based optical fibers [26, 27]. This silica segmented-cladding fiber can maintain single-mode operation with a large core size via the effective index difference between the solid core and the average index of the two materials used in the segmented cladding. However, the “segmented-cladding” silica fiber cannot be applied in harsh high temperature working environments. Analysis and theory in their study is limited to weakly guiding fiber (i.e., $n_1 \approx n_2$). In our study, single crystal sapphire optical fiber (SCSF) with a “windmill” core may be able to be fabricated by masking and etching in a solution of sulfuric and phosphoric acid [28].

This research encompassed the numerical and experimental approach to determine the structure parameters in a new fiber structure of the single crystal sapphire optical fiber (SCSF) named the “windmill” single crystal sapphire optical fiber (SCSF), and elucidated how they influence the resultant number of modes in the fiber. The approach used the Finite Element Analysis (FEA), which is based on numerical simulation, and demonstrated that the “windmill”
single crystal sapphire optical fiber (SCSF) can exhibit single-mode operation with a relatively large core diameter. This research also included the fabrication of the bundled “windmill” single crystal sapphire optical fiber (SCSF) by the Laser-heated Pedestal Growth (LHPG) method. Materials presented cover the background information with respect to the Finite Element Analysis (FEA) based numerical approach on the fiber structure design and optimization and the Laser-heated Pedestal Growth (LHPG) fabrication process. This research did not consider the chromatic dispersion associated with the refractive index of the material. This work focused exclusively on understanding the effects induced by the special geometry on the mode volume reduction.
2. Theoretical Background

2.1. Mode volume reduction in Optical Fiber

An optical fiber is a cylindrical dielectric waveguide made of low loss material. It has a central core in which the light is guided, embedded in an outer cladding of slightly lower refractive index. One of the concepts that can be used to describe the light propagation mechanisms is called Total Internal Reflection (TIR) which occurs at the boundary between two media of different refractive indexes [29]. Based on Snell’s Law, light rays incident on the core-cladding boundary at angles greater than the critical angle undergo TIR and are guided through the core without refraction into the cladding. The condition for the rays to always undergo the TIR is that its angle with respect to the z axis be smaller than the critical angle.

Fibers of high chemical purity are used to guide light for tens of kilometers with relatively low loss of optical power. Figure 1 demonstrates the TIR in an optical fiber. The refractive indices of the core and cladding in the fiber are $n_1$ and $n_2$, respectively, and the refractive index of air is 1. As shown in Figure 1, the acceptance angle $\alpha$ of the fiber determines the cone of external rays that are guided by the fiber, and the angle $\theta_c$ is critical angle. Thus, $\alpha$ defines an acceptance cone for an optical fiber, and the Numerical Aperture (NA) in an optical fiber is given by Eq. 1 [29].

\[
NA = \sin \alpha = \sqrt{n_1^2 - n_2^2}
\]

Eq. 1
Figure 1. TIR, acceptance angle and critical angle of an optical fiber.

The light propagation in an optical fiber can also be explained by electromagnetic (EM) optics theory. An EM field is described with two related vector fields. And these two fields, the electric field E and the magnetic field H are a function of position and time. Maxwell’s Equations (Eq. 2) and the Helmholtz Equation (Eq. 3) are used to describe the light propagation in an optical fiber under an EM field [29].

\[
\nabla \times H = \varepsilon \frac{\partial E}{\partial t} \tag{Eq. 2}
\]

\[
\nabla \times E = -\mu \frac{\partial H}{\partial t}
\]

(Linear, nondispersive, homogenous, isotropic, source-free medium)

\[
\nabla \cdot H = 0
\]

\[
\nabla \cdot E = 0
\]

\[
\nabla^2 u - \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2} = 0 \tag{Eq. 3}
\]
Where \( E \) is the electric field, \( H \) is the magnetic field, \( \varepsilon \) is the electric permittivity, \( \mu \) is the magnetic permeability, \( u \) can be the electric field or the magnetic field, and \( c \) is the speed of light.

In the cylindrical coordinate system (Figure 2), and assuming that the wave is traveling along the \( z \) direction, the Helmholtz equation can be written as [29],

\[
\frac{\partial^2 U}{\partial r^2} + \frac{1}{r} \frac{\partial U}{\partial r} + \frac{1}{r^2} \frac{\partial^2 U}{\partial \phi^2} + \frac{\partial^2 U}{\partial z^2} + n^2 k_0^2 U = 0 \quad \text{Eq. 4}
\]

\[
U(r, \phi, z) = u(r) e^{-jl\phi} e^{-j\beta z}, \quad l = 0, \pm 1, \pm 2, \ldots \quad \text{Eq. 5}
\]

\[
\frac{d^2 u}{dr^2} + \frac{1}{r} \frac{du}{dr} + \left( n^2(r) k_0^2 - \beta^2 - \frac{l^2}{r^2} \right) u = 0 \quad \text{Eq. 6}
\]

Figure 2. The schematic of the cylindrical coordinate system in an optical fiber. Reprint from *Fundamentals of Photonics, 2nd Edition* (Figure 9.2-1), By Bahaa E. A. Saleh, Malvin Carl Teich, Wiley Books. Copyright (2007) by Wiley Books.

Where \( U \) is a function of \( r, \phi \) and \( z \). \( r \) is the core radius, \( n \) is the refractive index, \( k_0 \) is the vacuum wavenumber and \( k_0 = 2\pi/\lambda_0 \). The propagation constant is \( \beta \), therefore the \( z \)-direction dependence of \( U \) is given by \( e^{-j\beta z} \). Since the period in the angle \( \phi \) is \( 2\pi \), it has the harmonic form \( e^{-jl\phi} \), where \( l \) is an integer representing the periodicity of the function.
The light propagation needs to satisfy the conditions given by both Maxwell’s equation and the Helmholtz equation, and the fields that satisfy this condition are called the modes of the fiber. These modes define the way the wave travels through space, for example, how the wave is distributed in space. The V parameter governs the number of modes in the fiber (Eq. 7). And the V parameter is directly proportional to the product of the radius-to-wavelength ratio and the numerical aperture NA.

\[ V = 2\pi \frac{r}{\lambda_0} NA \]  

Eq. 7

And, the number of modes for fibers with large V parameters can be approximated by [29],

\[ M \approx \frac{4}{\pi^2} V^2 \]  

Eq. 8

Eq. 7 indicates that in the weakly guiding fiber (i.e., \( n_1 \approx n_2 \)), the number of modes (M) for fibers with large V parameter is directly proportional to the fiber radius and numerical aperture (NA). In optical fibers, the mode volume refers to the number of bound modes (also known as guided modes) that an optical fiber is capable of supporting. The guided modes are confined to the core, and propagate energy along the fiber, transporting information and power. Therefore, for a given wavelength, the reduction in the mode volume can be achieved by reducing the radius and/or the NA of the optical fiber.

A single-mode optical fiber (SMF) is an optical fiber designed to carry only one mode. The SMF operation is achieved via a small core diameter and a small NA, or by operating at a sufficiently low optical frequency. There are numerous advantages of using a SMF. For example, since there is only one mode with one group velocity, a SMF can eliminate the modal dispersion caused by the group velocity delay distortion. Moreover, a SMF also eliminates the modal noise from
random interference of the modes, which happens due to uncontrollable imperfection, strains, and temperature fluctuations. On the other hand, multimode fibers (MMF) are optical fibers which support multiple guided modes for a given optical frequency and polarization.

In both SMF and MMF, there are two independent configurations of the E and H vectors for each mode, which correspond to the two states of polarization. The solutions of Eq. 6 are the family of Bessel functions, and these functions lead to a characteristic equation for β with the ratio \( a/\lambda_0 \) and the fiber indexes \( n_1, n_2 \) as the known parameters. For each azimuthal index \( l \), the characteristic equation (Eq. 9) has multiple solutions yielding discrete propagation constant \( \beta_{lm} \), and each solution represent a mode. In Eq. 9, \( J_l(x) \) is the Bessel Function of the first kind and order \( l \), and \( K_l(x) \) is the modified Bessel function of the second kind and order of \( l \). In addition, \( X=k_T R \), \( Y=\gamma R \), \( R \) is the core radius, the parameters \( k_T \) and \( \gamma \) determine the rate of change of \( u \) in the core and in the cladding, respectively. A large value of \( k_T \) indicate more oscillation of the radial distribution in the core. A large value of \( \gamma \) means more rapid decay and smaller penetration of the wave into the cladding [29]. In general, coupling of the longitudinal components of E and H are required by the boundary condition. The boundary conditions require that the tangential components of \( E_\phi \) and \( E_z \) of E inside and outside of the dielectric interface at \( r=R \) must be the same. If the boundary conditions do not lead to coupling between field components, mode solutions can be obtained in either \( E_z=0 \) or \( H_z=0 \). When \( E_z=0 \) the modes are called TE (transverse electric) mode, and when \( H_z=0 \) the modes are called TM (transverse magnetic) mode. If both \( E_z \neq 0 \) and \( H_z \neq 0 \), the modes are called as HE or EH modes, depending on whether \( E_z \) or \( H_z \) makes a larger contribution to the transverse field[30].

In most fibers, the guided rays are paraxial due to the weakly guiding. Therefore, the longitudinal components of the electric and magnetic fields are far weaker than the transverse
components and the guided waves are approximately transverse electromagnetic in nature. The linear polarization in the x and y directions then forms an orthogonal state of polarization. Therefore, a mode can be described by the index \( l \) and \( m \), which characterizes the azimuthal and radial distribution respectively [29]. The linear polarized \((l, m)\) mode is usually denoted as the \(LP_{lm}\) mode. The two polarization modes travel with the same propagation constant and spatial distribution. Thus, the modes found by solving the Maxwell and Helmholtz equations in a weakly guiding fiber can be assumed to be linear polarized (LP) modes. These linear polarized (LP) modes are good approximations of TE, TM HE and EH modes in a weakly guiding fiber. Figure 3 illustrates the electric field directions of the six lowest-order polarization modes of a MMF. A part of the guided linear polarized (LP) modes for a MMF are given in Figure 4. The simplest of all these modes is named the fundamental mode, and also called the \(LP_{01}\) mode.

\[
\frac{XJ_{l\pm 1}(X)}{J_l(X)} = \pm Y \frac{K_{l\pm 1}(Y)}{K_l(Y)}, \quad Y = \sqrt{V^2 - X^2}
\]

Eq. 9

![Figure 3. Electric field directions of the six lowest-order polarization modes in a MMF [31]. Reprint from A. Witkowska, S. G. Leon-Saval, A. Pham, and T. A. Birks, "All-fiber LP11 mode converters," Opt. Lett. 33, 306-308 (2008).](image-url)
Figure 4. Electric field amplitude profiles for part of the guided modes of a MMF [32]. Source: RP Photonics Consulting GmbH, generated with the RP Fiber Power software.
2.2. Confinement Loss and Perfect Matched Layer

In general, the modeling of optical fibers takes advantages of the fact that the E and H field can be decomposed into longitudinal and transverse components in the waveguide with invariant index profiles along the z-direction. This field can be expressed as [33]:

\[
\xi(x, y, z, t) = \{\xi_t(x, y) + \xi_z(x, y)\}e^{-j(\omega t - \beta z)}
\]

Where \(\xi\) denotes the E or H field and the subscript t and z denote the transverse and longitudinal components respectively, and \(\omega\) is the angular frequency. The leakage loss of a particular mode can be represented by the imaginary part of the complex propagation constant \(\beta\). A special boundary condition of the computational domain, a Perfect Matched Layer (PML), is applied to calculate \(\beta\). A PML is a layer surrounding the computational domain, which can theoretically absorb without reflecting any kind of wave traveling towards the boundaries [34]. The Confinement loss (CL) of an optical fiber can be estimated by employing a PML. For light propagating along the z direction, Maxwell’s equations for an optical waveguide with an anisotropic-type PML boundary condition are expressed as Eq. 11[33] and Eq. 12[35] with the PML matrix given by Eq. 13.

\[
jk_0se_xE = \nabla \times H
\]

\[
-jk_0s\mu_xH = \nabla \times E
\]

\[
\nabla \times (s^{-1}\nabla \times E) - k_0^2n^2sE = 0
\]

\[
\nabla \times \left(\frac{1}{n^2}s^{-1}\nabla \times H\right) - k_0^2sH = 0
\]
\[
\begin{bmatrix}
\frac{s_y}{s_x} & 0 & 0 \\
0 & \frac{s_x}{s_y} & 0 \\
0 & 0 & s_x s_y
\end{bmatrix}
\]

Eq. 15

\[
s_x = 1 - \frac{\sigma_x}{j\omega \varepsilon_0}, 
\quad s_y = 1 - \frac{\sigma_y}{j\omega \varepsilon_0}
\]

Where, \(E\): electric field; \(H\): magnetic field; \(\beta\): complex propagation constant; \(k_0\): the wave number in the vacuum; \(\varepsilon_r\): relative dielectric permittivity; \(\mu_r\): relative magnetic permittivity; \(s\): PML matrix; \(\sigma\): conductivity profile; \(\varepsilon_0\): free space dielectric permittivity.

Substituting Eq. 15 into Eq. 14, eigenvalue equations can be obtained for the E and H field as in Eq. 14[33]:

\[
\begin{bmatrix}
P_{xx} & P_{xy} \\
P_{yx} & P_{yy}
\end{bmatrix}
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix}
= \beta^2
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix}
\]

Eq. 16

\[
\begin{bmatrix}
Q_{xx} & Q_{xy} \\
Q_{yx} & Q_{yy}
\end{bmatrix}
\begin{bmatrix}
H_x \\
H_y
\end{bmatrix}
= \beta^2
\begin{bmatrix}
H_x \\
H_y
\end{bmatrix}
\]

Further detail regarding the \(P\) and \(Q\) matrices can be found in reference [33]. Solving the eigenvalue equations in Eq. 16 the propagation constant \(\beta\) can be obtained in a complex form:

\[
\beta = Re(\beta) + Im(\beta)
\]

Eq. 17

Where \(Re(\beta)\) and \(Im(\beta)\) are the real and imaginary part of \(\beta\). Thus the Confinement loss (CL) can be calculated by [33, 36, 37]:

\[
CL = 8.686 Im(\beta)
\]

Eq. 18
2.3. Numerical Analysis

Due to the complex calculation in the eigenvalue equations, an advanced numerical technique combined with the Finite Element Method (FEM) were used to perform comprehensive analyses in this study.

A modified eigenvalue equation is applied in the Finite Element Method (FEM) analysis:

\[ \nabla \times (\mu^{-1} \nabla \times E) - \lambda E = 0 \]  

Eq. 19

Where,

\[ \lambda = k_0^2 (\varepsilon_r - \frac{j\sigma}{\omega}) \]

Here, \( \lambda \) is the eigenvalue, \( \sigma \) is the electrical conductivity. For the time-harmonic problem, the electric field for out-of-plane propagation can be written as:

\[ E(r, t) = Re(\vec{E}(r)e^{j\omega t - \beta z}) \]  

Eq. 20

Where, \( \vec{E} \) is a phasor and \( z \) is the known out-of-plane direction.

And,

\[ \beta = Re(\beta) + Im(\beta) = -\lambda \]  

Eq. 21

Where \( Re(\beta) \) and \( Im(\beta) \) are the real and imaginary part of \( \beta \).

And the Confinement loss (CL) can be calculated by [33, 36, 37]

\[ CL = 8.686 Im(\beta) \]  

Eq. 22
A direct linear system solver (UMFPACK) was implemented to complete the modal analysis by solving near the effective index of the single crystal sapphire optical fiber (SCSF) for a discrete number of modes. All the simulations were performed through a number of iterations until a solution converged that met a defined error limit.

3. Fiber Design, Optimization and Analysis

In this work, the Confinement loss (CL) of the optical fiber was estimated via the implementation of the Finite Element Method (FEM) in the commercial software package COMSOL Multiphysics®. There were two related research works described in this section.

Section 3.1 demonstrates the design of the “windmill” single crystal sapphire optical fiber (SCSF), the parameter selection in the “windmill” single crystal sapphire optical fiber (SCSF) and the simulation domain with the PML layer. The main purpose of this numerical simulation was to evaluate the influence of the fiber diameter and cladding parameters on the mode volume reduction and the Confinement loss (CL) of the fundamental mode. The incident wavelength in this section was chosen at 532nm, which was preferred in the Raman distributed sensing systems. In the Raman distributed sensing systems, the blackbody radiation yields a strong and stable background at high temperature (Figure 5), making it difficult to distinguish a weak signal. In addition, Raman scattering intensity was inversely proportional to the fourth power of the wavelength. Considering the transmission window of single crystal sapphire optical fiber (SCSF), Raman scattering intensity and fiber attenuation, a laser wavelength of 532nm was chosen to avoid the blackbody radiation as well as maintain an acceptable fiber attenuation [38].
At an incident wavelength of 532 nm, the refractive index of the core (SCSF) and cladding (air) are 1.7717 and 1.0 [39].

Figure 5. Blackbody radiation curves [40]. Reprint from Thermal Infrared Remote Sensing: Theoretical Background of Thermal Infrared Remote Sensing (Figure 1.5), By Claudia Kuenzer, Springer. Copyright (2013) by Springer.

Section 3.2 will discuss the “windmill” single crystal sapphire optical fiber (SCSF) design with single-mode operation in the spectral range from 0.4μm to 2μm. In this section, an effective single-mode “windmill” single crystal sapphire optical fiber (SCSF) will be discussed. Additionally, the single-mode operation condition has been controlled by tailoring the “windmill” parameters. The refractive index of sapphire in the studied spectral range follows the Sellmeier equation [41].
3.1. “Windmill” single crystal sapphire optical fiber (SCSF)

Considering the difficulty in fabricating a cladding on single crystal sapphire fibers in order to produce a single mode fiber, a new type of single crystal sapphire optical fiber (SCSF) design was proposed to reduce the number of guided modes via a highly dispersive cladding with a periodic array of high and low index regions in the azimuthal direction. The structure retains a “core” region of pure single crystal sapphire optical fiber (SCSF) in the center of the fiber and a “cladding” region of alternating layers of air and single crystal sapphire optical fiber (SCSF) in the azimuthal direction that was uniform in the radial direction.

The “windmill” fiber with diameter \(d\) has 10 elliptical holes with semi-major axis \((a)\) and semi-minor axis \((b)\) radially distributed around the core (Figure 6 (a)). Figure 6(b) shows the variations of the “windmill” core structure with a different \(a\) (\(\mu m\)) and \(b\) (\(\mu m\)) combination for a 5\(\mu m\) diameter core fiber. The objective of the work in this section was to model the propagation characteristics of a “windmill” single crystal sapphire optical fiber (SCSF) with different semi-major and semi-minor axis under the invariant fiber diameter. This process would then allow for easy modification of semi-major and semi-minor parameters of the single crystal sapphire optical fiber (SCSF) with studied diameter, in order to further analyze how the structure parameters influence the confinement loss. Figure 7 shows the same “windmill” single crystal sapphire optical fiber (SCSF) structure given by Figure 6 in a simulation environment. The outer layer of the fiber with blue color was set as the PML.
Figure 6. Structure of SCSF with a “windmill” core (a); “windmill” fiber (d=5μm) with different α and β parameters (b); fundamental mode energy pattern in the E field “windmill” fiber with d=5μm, α=1.5μm, β=0.2μm (c).

Figure 7. “Windmill” SCSF (in Figure 6) in the simulation environment.
3.1.1. Mode volume reduction

The number of modes in conventional single crystal sapphire optical fiber (SCSF) with diminishing diameter calculated by Eq. 8 was given in Figure 8 (a). The influence of $a$ and $b$ on the guided modes for “windmill” fiber with diameters of 70μm, 50μm, 30μm, 10μm and 5μm was shown in Figure 8 (b)-(f). As expected in the conventional fiber, the guided modes in the fiber decrease with a corresponding decrease in diameter. For the “windmill” fiber, the number of guided modes was plotted with increasing $a$ for three values of $b$. A comparison of the number of modes between all five fibers was given in Figure 8. The number of guided modes for 70μm, 50μm, 30μm, 10μm, 5μm conventional fibers were significantly reduced by the “windmill” core structure with the highest $a$ and lowest $b$ combination. It was also observed that the $a$ value has a significant influence on the number of modes in a “windmill” fiber at the studied wavelength. As the $a$ increases, the effective core size decreases and, therefore, the number of guided modes was reduced. On the other hand, because of the small $b$ value, a decrease in the effective index difference between the core and cladding reduces the NA, which decreases the number of modes propagating in the fiber’s core. These effects also can be explained by radial-effective-index method in a previous study on silica fibers [26].
Figure 8. Number of guided modes in conventional fiber with diminishing diameter (a); a “windmill” fiber with combination of $\alpha$ and $b$ for 70$\mu$m diameter (b); 50$\mu$m diameter (c); 30$\mu$m diameter (d); 10$\mu$m diameter (e); 5$\mu$m diameter (f).
3.1.2. Confinement loss of the fundamental mode

Structure parameters \((d, a \text{ and } b)\), number of modes \((M)\), effective index of fundamental mode \((n_f)\) and confinement loss \((CL)\) of the fundamental mode for a “windmill” fiber with the smallest number of modes in each diameter are given in Table 2. The number of modes was significantly reduced from over thousand to less than 4 modes on each studied fiber. Confinement loss \((CL)\) increases with decreasing fiber’s diameter in 0.532\(\mu\)m wavelength. Since the \(V\) number decreased with decreasing fiber diameter, less modes will be supported in the core and the core will have less confinement capability. Compared with the loss in conventional single crystal sapphire optical fiber (SCSF) \((-10^3 \text{ dB/km [3]})\), Confinement loss \((CL)\) in the “windmill” single crystal sapphire optical fiber (SCSF) was negligible. Thus, with a proper design, the mode volume of single crystal sapphire optical fiber (SCSF) could be significantly reduced while maintaining low Confinement loss \((CL)\).

Table 2 Structure parameters and Confinement loss \((CL)\) of the fundamental mode for “windmill” fibers in each group

<table>
<thead>
<tr>
<th>d((\mu)m)</th>
<th>a ((\mu)m)</th>
<th>b ((\mu)m)</th>
<th>M</th>
<th>n_f</th>
<th>CL (dB/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>25</td>
<td>2</td>
<td>3</td>
<td>1.7716</td>
<td>4.00\times10^{-10}</td>
</tr>
<tr>
<td>50</td>
<td>15</td>
<td>2</td>
<td>3</td>
<td>1.7716</td>
<td>1.56\times10^{-9}</td>
</tr>
<tr>
<td>30</td>
<td>9</td>
<td>1.2</td>
<td>3</td>
<td>1.7714</td>
<td>1.03\times10^{-9}</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>0.2</td>
<td>3</td>
<td>1.7696</td>
<td>2.22\times10^{-8}</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>0.2</td>
<td>2</td>
<td>1.7633</td>
<td>1.62\times10^{-7}</td>
</tr>
</tbody>
</table>
3.1.3. Refractive index as a function of wavelength

The refractive index of single crystal sapphire as a function of wavelength follows the *Sellmeier equation*:

\[
    n^2 - 1 = \sum_i \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2}
\]

Eq. 23

The coefficients were given in the previous study [41], and plot in Figure 9 by a dashed line. The spectral range, in our study, was from 0.24μm to 2μm. The studied “windmill” single crystal sapphire optical fiber (SCSF) has a diameter of 5μm, with a=1.5μm and b=0.2μm. Based on the *Sellmeier equation*, the refractive indices of the fundamental mode (solid line) and the 2nd order mode (dash dot line) in the “windmill” single crystal sapphire optical fiber (SCSF) as a function of wavelength were shown in Figure 9. The electric field of the fundamental mode and the 2nd order mode in the “windmill” single crystal sapphire optical fiber (SCSF) at 0.24μm and 2μm were inserted in Figure 9. The inserted images clearly demonstrate that at 0.24μm wavelength the electric field does not extend into the “windmill” cladding, contrary to what occurs at 2μm wavelength. Simulation in the spectral range confirms that the longer the wavelength, the more extension of the field into the cladding. Due to the behavior of the electric field towards the cladding on the “windmill” structure, the 2nd order mode becomes lossy when the wavelength increases.
Figure 9. Refractive index for SCSF and “windmill” SCSF as a function of wavelength. Electric filed distribution for “windmill” SCSF at wavelength of 0.24μm and 2μm were inserted.
3.2. Single mode optical fibers

A pure Silica Core Fiber was developed in the 1980's and was mainly used for submarine optical cable applications or other R&D activities in which extremely low attenuation is required. SMF has a small core diameter that allows only one mode of light to propagate. Because of this, the number of light reflections created as the light passes through the core decreases, lowering attenuation and creating the ability for the signal to travel further. One of the well-known commercial SMF silica based fibers is the SMF 28® Ultra optical fiber from Corning Incorporated®, which has a typical attenuation less than 0.18dB/km at 1550nm. This fiber has a Ge doped silica core with diameter of 8.2μm and a pure silica cladding with diameter of 125μm [42]. The measured NA at 1310nm is 0.14. As discussed earlier, a fiber with core radius r and numerical aperture NA operates as a single mode fiber in the fundamental LP_{01} mode if \( V < 2.405 \). Single-mode operation is achieved via a small core diameter and small NA \( (n_1 \approx n_2) \), or by operating at a sufficiently low spectrum wavelength [29]. In the commercial silica SMF, the single-mode operation is achieved by a small core size (8.2μm) and slightly refractive index difference between a Ge doped silica core and a pure silica cladding.

In the previous section, a new single crystal sapphire fiber design which has been referred to as the “windmill” shaped single crystal sapphire optical fiber (SCSF) was proposed and demonstrated a dramatic reduction of mode volume [43]. The effective single-mode operation was achieved by choosing the fiber parameters to induce high leakage loss for the higher-order mode (HOM), while maintaining low leakage loss for the fundamental mode (FM) [44-47]. Unlike the commercial silica SMFs, the single-mode operation in the “windmill” single crystal sapphire optical fiber (SCSF) was not dependent on the core size and NA but the structure
induced leakage loss. A Finite Element Analysis (FEA) based numerical simulations demonstrated that with appropriate parameters, the leakage loss of the higher-order mode (HOM) was three orders of magnitude higher than that of the fundamental mode (FM). Such a fiber exhibits single-mode operation by stripping-off the higher-order mode (HOM) while maintaining the fundamental mode (FM) over a long propagation distance. This section was focused on the study of an effective single-mode “windmill” single crystal sapphire optical fiber (SCSF), and demonstrates that the single-mode operation condition controlled by tailoring the “windmill” parameters.

3.2.1. Optimized structure of single mode “windmill” single crystal sapphire optical fiber (SCSF) with large core size

To find the optimum number of elliptical holes (N) for the “windmill” single crystal sapphire optical fiber (SCSF), simulations were performed under identical condition while changing N from 4 to 20 for fibers studied in Table 2 (Figure 10). At the wavelength of 532nm, electric field distribution on “windmill” single crystal sapphire optical fiber (SCSF) with d=50μm, a=15μm, b=2μm and different N were given in Figure 11 to Figure 14. Figure 11 shows the simulation results of the first mode in “windmill” single crystal sapphire optical fiber (SCSF) with N=4. As shown in this figure, the electric field could not be confined in the core regain but distributed in the cladding regions. Therefore, a “windmill” single crystal sapphire optical fiber (SCSF) with N=4 cannot be used as a waveguide at the studied wavelength. Figure 12 shows the simulation results of the first three modes in “windmill” single crystal sapphire optical fiber (SCSF) with N=6. As shown in this figure, the electric field was confined inside the core region for the FM (Figure 12 (A)) and the next higher-order mode (HOM) (Figure 12 (B)). The electric field also can be found outside the core region and created a cladding mode, as
shown in Figure 12 (C). As N increased above 6, there were more than one higher-order mode (HOM) confined in the core. Figure 13 shows the fundamental mode (FM) (Figure 13 (A)) and next three higher-order mode (HOM) (Figure 13 (B)) at N=8 in the “windmill” single crystal sapphire optical fiber (SCSF). The larger the N the more higher-order mode (HOM) confined in the core of a “windmill” single crystal sapphire optical fiber (SCSF). Finally, the “windmill” single crystal sapphire optical fiber (SCSF) became highly multimode when N was reached 20. Figure 14 shows the electric field distribution of fundamental mode (FM) (Figure 14 (A)) and one of the higher-order mode (HOM) (Figure 14 (B)) in a “windmill” single crystal sapphire optical fiber (SCSF) with N=20.

These simulations predicted that the number of guided modes increases significantly with an increase in N. This can be understood from the fact that more segments (at fixed d, a and b) lower the effective cladding index, which in turn increases the refractive index difference between the core and cladding. The subsequent increase in numerical aperture allows the fiber to guide a larger number of modes. In order to achieve mode volume reduction by the “windmill” single crystal sapphire optical fiber (SCSF) as a waveguide, two facts need to be considered. Firstly, this “windmill” single crystal sapphire optical fiber (SCSF) should be able to guide the fundamental mode (FM). Apparently, if the fiber cannot support the fundamental mode (FM), it cannot be used as a waveguide. Secondly, the higher-order mode (HOM) should be as small as possible, and this was also the ultimate goal of this research. As indicated earlier, a large N can introduce more higher-order mode (HOM) to the fiber and lead to a highly multimode single crystal sapphire optical fiber (SCSF). Therefore, the optimum N number in the “windmill” single crystal sapphire optical fiber (SCSF) should be able to support the fundamental mode (FM) as well as the minimum number of the higher-order modes (HOMs). In an effort to assure a fully
symmetric structure, it was found that the optimum number of allowable elliptical holes for the “windmill” sapphire fiber was 6. Therefore, in this study, we focused on the 6 elliptical holes “windmill” single crystal sapphire optical fiber (SCSF). The cross section of the proposed fiber design was shown in Figure 15. The “windmill” single crystal sapphire optical fiber (SCSF) with the diameter $d$ has 6 elliptical holes with semi-major axis $a$ and semi-minor axis $b$.

![Figure 10. “Windmill” SCSF design with different N parameter at fixed $d$, $a$ and $b$ parameters.](image1)

![Figure 11. First mode in the “windmill” SCSF with N=4.](image2)
Figure 12. First three modes in the “windmill” SCSF with N=6.
Figure 13. First four modes in the “windmill” SCSF with $N=8$.

Figure 14. The fundamental mode (A) and the high order mode (B) in the “windmill” SCSF with $N=20$. 
As shown in Figure 12, both the fundamental mode (FM) and the higher-order modes (HOMs) can extend into the cladding region and become a leaky mode. However, we can construct a high differential leakage between the fundamental mode (FM) and the higher-order modes (HOMs) by tailoring the semi-major axis (a) and semi-minor axis (b) in the “windmill” structures. A high differential leakage loss between the fundamental mode (FM) and higher-order mode (HOM) ensures single mode operation in the “windmill” single crystal sapphire optical fiber (SCSF). Therefore, the cladding design can be tailored to increase the higher-order mode (HOM) leakage loss that was sufficiently higher than that of the fundamental mode (FM). Therefore, single mode operation can be achieved in an optical fiber by quickly stripping-off the higher order modes, while maintaining the fundamental mode (FM) over the desired propagation distance. This is different from the single-mode operation mechanism in commercial silica SMF. As discussed on the silica SMF, the diameter of the core is fairly small relative to the cladding and NA is far less than 1. Because of this, when light enters the fiber-optic cable, it propagates down toward the end in just a single mode, which is the lowest-order mode. Hence, this lowest order mode is confined in the core, however, the higher order modes are absent. In all cases, we do not consider material loss, surface roughness and the chromatic dispersion associated with the refractive index of the material. We focus exclusively on understanding the influence of the unique geometry on the propagation of the modes, which can be evaluated via confinement loss (CL)[43].
3.2.2. Single-mode operation

The effective-single mode operation in the “windmill” single crystal sapphire optical fiber (SCSF) can be achieved by evaluating $a$ and $b$ parameters for different diameters, $d$, to induce a high Confinement loss (CL) for the higher-order mode (HOM) and a low Confinement loss (CL) for the fundamental mode (FM). To evaluate the feasibility of single mode operation, it was sufficient to calculate the Confinement loss (CL) of the first two modes, since the Confinement loss (CL) of the modes increases with their mode order for the chosen fiber structure. A high difference between higher-order mode (HOM) and fundamental mode (FM) ensures effective single-mode operation in this “windmill” single crystal sapphire optical fiber (SCSF) fiber. In reality, it was easier to fabricate a “windmill” single crystal sapphire optical fiber (SCSF) with small $a$ and large $b$ parameter. Thus, in this study, we design and analyze the “windmill” single crystal sapphire optical fiber (SCSF) with optimized parameters for effective single-mode operation.
As shown in Figure 16, under the invariant semi-major axis $a$ value, the shape of the “windmill” fiber’s core (the dashed circle) becomes more circular with a large $b$ value (Figure 16 (B)) compared with small $b$ value (Figure 16 (A)). The high circularity geometry of the core region in the “windmill” fiber, which resulting in a high possibility of TIR in the core, greatly reduces the confinement losses of individual modes. On the other hand, with the invariant semi-minor axis $b$ value, the effective core size shrinks with the large $a$ value. As shown in Figure 17 (A) and (B), the effective core diameter $d'$ (the dashed circle) shrinks and the cladding region increases, which reduces the Confinement loss (CL) of the studied modes for most cases. As shown in Figure 18, the effects of parameters $a$ and $b$ on the Confinement loss (CL) of fundamental mode (FM) (in solid line) and higher-order mode (HOM) (in dashed line) in the “windmill” single crystal sapphire optical fiber (SCSF) with diameter of 70μm (Figure 18 (a)), 50μm (Figure 18 (b)) and 30μm (Figure 18 (c)). The figures indicate that the Confinement loss (CL) of both modes decrease with $b$.

![Figure 16](image1.png)

Figure 16. “Windmill” structure with a small semi-minor axis $b$ (A) and a large semi-minor axis $b$ (B).
Figure 17. “Windmill” structure with a small semi-major axis $a$ (A) and a large semi-major axis $a$ (B).

At a wavelength of 532nm, the optimized parameters for the “windmill” single crystal sapphire optical fiber (SCSF) with a diameter of 70µm were found to be $a = 28\mu m$ and $b=6\mu m$. Compared with Confinement loss (CL), 0.11 dB/m, of the fundamental mode (FM) the Confinement loss (CL) of higher-order mode (HOM) was significantly higher at 19.19 dB/m. Therefore, a 1.04 meter long waveguide can effectively strip off all the high order modes and ensure the single mode operation in a “windmill” single crystal sapphire optical fiber (SCSF). This was a distinct difference between a single mode “windmill” single crystal sapphire optical fiber (SCSF) and a commercial single mode silica fiber. In the commercial silica SMF, the single-mode operation has been achieved by a small core size and NA, hence none of the higher-order modes (HOMs) but only the fundamental mode (FM) could be confined in the core. The single mode “windmill” single crystal sapphire optical fiber (SCSF), on the other hand, did excite both fundamental mode (FM) and higher-order modes (HOMs) as the light coupled into the core. However, the higher-order modes (HOMs) were stripped off due to a high confinement loss and only left fundamental mode (FM) confined in the core.
Based on these results, the optimum parameters for a 50μm core diameter “windmill” single crystal sapphire optical fiber (SCSF) at 532nm were $a=18\mu m$ and $b=5\mu m$, with the Confinement loss (CL) of fundamental mode (FM) at 0.27 dB/m and higher-order mode (HOM) at 17 dB/m. The optimum parameters for a 30μm core diameter “windmill” single crystal sapphire optical fiber (SCSF) at 532nm were $a=11\mu m$ and $b=3\mu m$, with the Confinement loss (CL) of fundamental mode (FM) at 0.4dB/m and higher-order mode (HOM) at 97 dB/m. A 1.18 meter long fiber with 50μm diameter and a 0.2 meter long fiber with 30μm diameter “windmill” single crystal sapphire optical fiber (SCSF) can strip off all the high order modes and ensure the single mode operation under the wavelength of 532nm. The effective core diameter ($d'$) in fibers with diameters of 70 μm, 50 μm and 30 μm was 14μm, 14 μm and 8 μm respectively. Based on Eq. 7 and Eq. 8, at the wavelength of 532nm, the theoretical maximum diameter of a conventional single mode sapphire fiber was 0.491μm. Comparing between a conventional single mode single crystal sapphire optical fiber (SCSF) and a “windmill” single mode single crystal sapphire optical fiber (SCSF) at the wavelength of 532nm, the core size of a “windmill” single mode single crystal sapphire optical fiber (SCSF) was over 28 times larger than the conventional singe mode single crystal sapphire optical fiber (SCSF).
Figure 18. Variation of confinement loss of the FM (solid line) and higher-order mode (HOM) (dash line) as a function of the parameter $a$ and $b$ for a SCSF with diameter of (a) 70μm; (b) 50μm; (c) 30μm. The legend for example: FM_b2 means the fundamental mode at b=2μm.
3.2.3. Electric field distribution

The electric field contour plot of the optimized “windmill” single crystal sapphire optical fiber (SCSF) with the diameters studied at a wavelength of 532nm are given in Figure 19 with the fundamental mode (FM) on the top and the higher-order mode (HOM) on the bottom. As shown in the figure, the fundamental mode (FM) of the fibers were well confined in the core region while the great extension of the pattern into the cladding region of the higher-order mode (HOM) indicates their leaky behavior. The large leakage losses of the higher-order mode (HOM) in the studied fibers were reflecting by these electric field contour plots.

![Electric field contour plots](image)

Figure 19. Electric field contour plot of the optimized “windmill” SCSF on fundamental mode (FM) (top) and higher-order mode (HOM) (bottom) with diameter of (a) 70μm; (b) 50μm; (c) 30μm.
3.2.4. Confinement loss and refractive index as function of wavelength

In this work, the spectral range was from 0.4μm to 2μm. The electric field distributions on the studied “windmill” single crystal sapphire optical fiber (SCSF) at 0.4μm and 2μm with the optimized $a$ and $b$ parameters are shown in Figure 20(a) and (b), Figure 21(a) and (b) and Figure 22(a) and (b).

The black and white line contour plots demonstrate the electric field intensity distribution, where the intensity contours were spaced by 0.5dB. The electric field of the fundamental mode (FM) was mostly confined in the effective core region with a small portion extending into the cladding region. On the other hand, the higher-order mode (HOM) had a much more dispersed pattern, and a large portion of the electric field was distributed into the cladding region. It was clearly demonstrated that at the shorter wavelengths, the modal fields were more confined in the effective core region, contrary to what occurs at longer wavelengths. Simulation at the intermediate wavelength confirms that for a longer wavelength, the extension of the modal field into the cladding region was greater. The spectral variation of Confinement loss (CL) for the fundamental mode (FM) and higher-order mode (HOM) for the studied “windmill” fiber corresponding to $d=30μm, 50μm$ and $70μm$ were plotted in Figure 20(c), Figure 21(c) and Figure 22(c) respectively. These Confinement loss (CL) of fundamental mode (FM) (solid line) and higher-order mode (HOM) (dashed line) were both increased with wavelength due to more spread of the modal fields in the “windmill” cladding. The refractive index of the single crystal sapphire at different wavelengths follows the Sellmeier equation. The refractive indices of the fundamental mode (FM) (solid line) and higher-order mode (HOM) (dot line) in the “windmill” single crystal sapphire optical fiber (SCSF), and refractive index of the fundamental mode (FM)
in single crystal sapphire (dashed line) were shown in Figure 20(d), Figure 21(d) and Figure 22(d).
Figure 20. “Windmill” SCSF with 30μm diameter (a) electric field distribution at a wavelength of 0.4μm; (b) electric field distribution at a wavelength of 2μm; (c) confinement loss as a function of wavelength; (d) refractive index as a function of wavelength.
Figure 21. “Windmill” SCSF with 50μm diameter (a) electric field distribution at a wavelength of 0.4μm; (b) electric field distribution at a wavelength of 2μm; (c) confinement loss as a function of wavelength; (d) refractive index as a function of wavelength.
Figure 22. “Windmill” SCSF with 70μm diameter (a) electric field distribution at a wavelength of 0.4μm; (b) electric field distribution at a wavelength of 2μm; (c) confinement loss as a function of wavelength; (d) refractive index as a function of wavelength.
3.3. Bundled “Windmill” single crystal sapphire optical fiber (SCSF)

Considering the fabrication challenges in the “windmill” single crystal sapphire optical fiber (SCSF), we proposed an equivalent “windmill” structure named bundled “Windmill” single crystal sapphire optical fiber (SCSF). Figure 23 gives the structure of a bundled “windmill” single crystal sapphire optical fiber (SCSF). The six red dashed boxes indicate the equivalent elliptical holes in the “windmill” structure. $D$ was the bundled fiber diameter, $D1$ was the core diameter and $D2$ was stacking fiber’s diameter. To construct a bundled “Windmill” structure, a close packed structure was required. Figure 24 shows two possible four-layer bundle cladding “windmill” sapphire fibers with 6-ring (A) and 12-ring (B) structures. The regions with blue and gray color were sapphire and air respectively. To find the optimized structure, all the parameters were invariant excepted reducing the core diameter from 1.6μm to 0.4μm.

![Figure 23. Bundled “windmill” SCSF structure.](image)
Figure 24. Four-layer bundled “windmill” SCSF in simulation environment with (A) 6-ring structure and (B) 12-ring structure.

The fundamental mode of a conventional single crystal sapphire optical fiber (SCSF) with different core diameter was given in Figure 25. The single mode conventional single crystal sapphire optical fiber (SCSF) in this simulation has a core diameter around 500nm, which was in agreement with the theoretical calculation by Eq. 8.
Figure 25. Electric field distribution of fundamental mode (FM) of conventional SCSF with diameter of (A) 1.6μm (B) 1.4μm (C) 1.2μm (D) 1.0μm (E) 0.8μm (F) 0.6μm (G) 0.4μm.
Figure 26 shows a set of simulations on the four-layer 6-ring bundled “windmill” single crystal sapphire optical fiber (SCSF) with the core diameter varied from 1.6 to 0.4μm. At all the simulated diameters, the electric field could not be confined in the core but in both the core and the first cladding layer. However, the electric field could be confined in the center core and achieved the single mode operation with decreasing core diameter in the four-layer 12–ring bundled “windmill” single crystal sapphire optical fiber (SCSF) (Figure 27 and Figure 28). Theoretically, a single mode four-layer 12-ring bundled “windmill” single crystal sapphire optical fiber (SCSF) has a core diameter at 0.8μm (800nm), which is 1.6 times larger than the conventional single crystal sapphire optical fiber (SCSF). Comparing the four-layer 6-ring and 12-ring bundled “windmill” single crystal sapphire optical fiber (SCSF), the 12-ring bundle is a better substitution structure for the “windmill” single crystal sapphire optical fiber (SCSF).
Figure 26. Electric field distribution of fundamental mode (FM) of four-layer 6-ring “windmill” structure SCSF with the core diameter of (A) 1.6μm (B) 1.4μm (C) 1.2μm (D) 1.0μm (E) 0.8μm (F) 0.6μm (G) 0.4μm.
Figure 27. Electric field distribution of FM of 12-ring “windmill” structure SCSF with the core diameter of (A) 1.6μm (B) 1.4μm (C) 1.2μm (D) 1.0μm (E) 0.8μm (F) 0.6μm (G) 0.4μm.
Figure 28. Electric field distribution of higher-order mode (HOM) of 12-ring “windmill” structure SCSF with the core diameter of (A) 1.6μm (B) 1.4μm (C) 1.2μm (D) 1.0μm (E) 0.8μm (F) 0.6μm (G) 0.4μm.
The parameters were chosen based on the bundled “windmill” single crystal sapphire optical fiber (SCSF) with the idea that the smallest cladding fiber could be made by the acid etching process. In the simulation, the wavelength was chosen at 0.532μm, D1=14μm, D2=4.9μm, searching at 100 modes near the refractive index of sapphire (1.7717). To find the optimized structure, all the parameters were invariant except reducing the number of cladding layers from 4 to a single layer (Figure 29). The electric field distribution of the bundled “windmill” single crystal sapphire optical fiber (SCSF) with different stacking layers on the fundamental mode (FM) and the higher-order modes (HOMs) are shown in Figure 30, Figure 31, Figure 32 and Figure 33. Confinement losses in the units of dB/m verses number of stacking layers are given in Figure 34.
Figure 29. Bundled “windmill” SFSC with (a) 4 layers; (b) 3 layers; (c) 2 layers; (d) 1 layer.
Figure 30. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 4 layers bundled “windmill” SCSF.
Figure 31. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 3 layers bundled "windmill" SCSF.
Figure 32. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 2 layers bundled “windmill” SCSF.
Figure 33. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 1 layer bundled “windmill” SCSF.
The modes in the simulated structures can be divided into two categories: fundamental mode: $LP_{01}$ mode (Figure 30(a), Figure 31(a), Figure 32(a) and Figure 33(a)), high order modes (in the alphabetic order): $LP_{11}$, $LP_{21}$, $LP_{02}$ and $LP_{31}$ mode (Figure 30(b-e), Figure 31(b-e), Figure 32(b-e) and Figure 33(b-e)). After simulating 100 modes in the studied structure, only the fundamental mode (FM) and four higher-order modes (HOMs) were found to be confined in the fiber’s core region. Therefore, the bundled “windmill” single crystal sapphire optical fiber (SCSF) can significantly reduce the number of modes without the need for the complicated masking and etching processes. The confinement loss of the fundamental mode being as low as $10^{-9}$ dB/m indicates an excellent confinement capability of this design structure (Figure 34). Thus, based on our results, the bundled “windmill” single crystal sapphire optical fiber (SCSF) would be a good substitution for the “windmill” single crystal sapphire optical fiber (SCSF) produced by a masking and etching process.
Figure 34. Confinement loss on the studied modes in bundled “windmill” SCSF.
4. Fiber Fabrication Experimental Procedures

Single crystal sapphire fiber was fabricated by Laser-heated pedestal growth (LHPG) system, which was constructed in-house at Virginia Tech. The fibers were cleaved into twelve pieces approximately 3 inches long each. Then, they were cleaned in a series of steps and assembled in the 1 layer bundled “windmill” single crystal sapphire optical fiber (SCSF). The following sections contain a full description of the Laser-heated Pedestal Growth (LHPG) system design, single crystal sapphire optical fiber (SCSF) fabrication process, fiber bundling steps as well as optic analysis on modal volume reduction.

4.1. Single crystal sapphire optical fiber (SCSF) Fabrication by Laser-heated Pedestal Growth (LHPG) System

Among all the laser-heated crystalline fiber-pulling techniques in recent years, Laser-heated Pedestal Growth (LHPG) has become one of the most popular. The main advantages of this technique are its high pulling rates and the possibility to produce very high melting point single crystal materials[48]. Besides that, it is a crucible-free technique, which allows the pulling of high-purity single crystals and composite fibers, avoiding mechanical stress and contamination due to the crucible material during the solidification process. The advantages of this technique make it suitable for the current works where small, quick and low cost single crystal sapphire optical fiber (SCSF) were required for the bundled “windmill” structure.

4.1.1. Laser-heated Pedestal Growth (LHPG) system

Schematic drawing of the Laser-heated Pedestal Growth (LHPG) beam steering optics design and in chamber design are given in Figure 35 and Figure 37. The beam steering optics in the Laser-heated Pedestal Growth (LHPG) system was fixed onto an optical table. In the beam
steering optics design (Figure 36), a CO₂ laser (continuous wave (CW), λ = 10.6μm) with the laser cavity cooled by water was chosen in this work. He–Ne laser with a wavelength of 632.8nm used to track the CO₂ laser beam path and acts as a guide for the eye in the optical alignment. The laser beams were guided into a closed chamber and hit the reflexicon mirror (Figure 37), where they were converted into a cylindrical shell and guided to a parabolic mirror, and focused over the source material. CCD camera and monitor have a microscope attached to it, allowing the viewing of the molten zone and growing fiber. And the fiber's diameter was controlled by the computer control system after the monitor.
Figure 35. Schematic drawing of the Laser-heated Pedestal Growth (LHPG) out of chamber design.
Figure 36. Beam Steering Optics of the LHPG system.
Figure 37. Schematic drawing of the LHPG in chamber design[48]. Reprint from Laser-Heated Pedestal Growth of Oxide Fibers (Figure 13.2), by Marcello R.B. Andreeta, Springer. Copyright (2010) by Springer.

Figure 38 shows the mechanical pulling system with (A) Upper and (B) Lower linear stage with manual linear stage and the fiber chuck. The growth chamber optics including parabolic mirror, reflaxicon and scraper mirror are given in Figure 39. All the growth chamber optics were made of an aluminum alloy and polished to a mirror finish.
Figure 38. The (A) Upper and (B) Lower linear stage with manual linear stage and the fiber chuck.
Figure 39. (A) A Parabolic Mirror; (B) Reflaxicon and Scraper Mirror.

The whole Laser-heated Pedestal Growth (LHPG) system assembled in this work is shown in Figure 40. The optical table was protected by clear Acrylic cover, which was used to prevent scattering of the CO₂ laser as well as the dust contamination from the ambient environment.
4.1.2. Fiber pulling process in fiber growth chamber

The Laser-heated Pedestal Growth (LHPG) technique was basically a miniature floating-zone-like method where the heating element was substituted by a focused laser ring to generate the molten zone[46]. The source material (pedestals) used to grow single crystal sapphire optical fiber (SCSF) was prepared by cutting a previous bulk-grown crystal or by mixing the constituent powers. The seed was a small piece of single crystal material from which a large crystal of the same material typically was to be grown. The pulling process starts with basically four steps inside the growth chamber, as illustrated in Figure 41.

The first step was to align the seed and the pedestal mechanically, both centralized in the optical axis of the laser beam (I). The next step was to create a small molten zone on top of the pedestal, by turning on the laser and slowly increasing the laser power (II). In the following step
the seed was introduced into the liquid and a molten zone was formed (III). Finally, the fiber is pulled (IV). The feeding/pulling process was controlled by computer software along with the upper linear stage and the lower linear stage.

Figure 41. Schematic drawing of the four steps performed in the Laser-heated Pedestal Growth (LHPG) technique: (I) mechanical alignment of the seed and the pedestal and (II) creation of a small molten zone on the top of the pedestal. (III) The seed was then introduced in the liquid phase and there was creation of a molten zone. (IV) The fiber-pulling process begins[48]. Reprint from Laser-Heated Pedestal Growth of Oxide Fibers (Figure13.5), by Marcello R.B. Andreeta, Springer. Copyright (2010) by Springer.
4.1.3. Mechanical pulling system and control

The translation of the feed and the seed rod was controlled by the high precision stepper linear stage manufactured by Parker. The manual linear stage (Newport) and fiber’s chuck mounted on the Parker linear stage was shown in Figure 38. The manual linear stage gave a precise position control on the seed (Upper) and the feed (Lower). The seed and the feed were held by the chucks. To control this Parker linear stage, we used the vendor pre-installed Parker Automation Controller (PAC) software and a computer. This PAC was based on the programmable logic controller (PLC), which using the CODESYS software platform with PLCopen as the programming language. The PLCopen activities are based upon the IEC 61131-3 standard, the only global standard for industrial control programming.

During the sapphire fiber pulling, the Upper and Lower stages need to move together along the same direction but under the independent speed. Therefore, a control panel was created for the linear stages by programming on the PAC.

Figure 42 shows the Parker linear stages pulling control panel. In this control system, a virtual Master station used to “gear” the two stages (also known as “slave”) together. During the sapphire fiber pulling process, two stages moving at the same time with independent speed can be achieved. The pulling control panel included the power button, the gear button, speed input windows in the unit of μm/s, the moving direction button and two assistant buttons on the bottom of the panel.
Figure 42. The Parker linear stage fiber pulling control panel.

Figure 43 indicated the Setup Screen panel. The Setup Screen panel will appear after one click on the “Page next” button in the fiber pulling control panel. This Setup Screen panel was used to on load and adjustment the feed and seed on the linear stages. It has a power button, go home button, the moving direction buttons and also a speed input windows in the unit of mm/s.

The variables, function blocks and the codes used for this control panel were given in Appendices0, B and C.
4.1.4. Feed and Seed Preparation

The feed used in the fabrication was polycrystalline Al$_2$O$_3$ rod in a 325μm diameter (Photran, LLC). The seed was random orientation sapphire rod in a 0.0315" ± 0.0004" diameter and 5.5"±0.5" long (Insaco, Inc.). The seed and the feed mechanism comprises of a miniature pin chucks with four retaining jaws, which were used to hold the seed and the feed. The pin chucks were then attached to one end of a stainless steel rod. This rods were attached on the Upper and Lower linear stages where their movement was restricted to vertical motion by two precision machined alumina bars mounted on the side of the Upper and Lower stages. Single crystal sapphire fiber during growing process in LHPG growth chamber is shown in Figure 44.
4.1.5. Fiber Bundling

The estimated diameter of the as-drawn single crystal sapphire optical fiber (SCSF) will be around 115μm [48]. The fiber bundle consists of 13 fibers arranged in a one-layer “windmill” shape as shown in Figure 33. The fiber bundle has been produced by drawing a fiber funnel on a glass lathe to the right dimension as shown in Figure 45. Since we were going to use a one layer bundled “windmill” single crystal sapphire optical fiber (SCSF) design with 445μm OD for the bundle structure, so the ID of the silica funnel should be around 450μm to give enough space for the bundling process. Then, the fibers were adjusted to the “windmill” structure, tied by platinum wire to secure the bundle and to keep the bundle in the desired arrangement.

Figure 44. Single crystal sapphire fiber during growing process in LHPG growth chamber.
Figure 45. The fiber bundle has produced by a fiber funnel.

4.2. Optical Analysis

Directly counting the number of modes guided in a fiber was very difficult. However, there were many alternate ways to prove the mode volume reduction in the bundled “windmill” single crystal sapphire optical fiber (SCSF). The far-field projection makes it easier to visualize the radial intensity distribution of light propagating along an optical fiber.

4.2.1. Far-Field Projection Measurement

The far-field radiation pattern shows the distribution of irradiance as a function of angle with the z-axis of the fiber at a certain distance (over 2 wavelength) from the fiber end face. It represents the radial intensity distribution of light travelling through an optical fiber. However, not all of the supported modes will be excited by a single wavelength laser source and the measured far-field pattern cannot represent the entire mode volume information in the optical fiber. Although the far-field pattern has its limitations, it does represent accurate overall of the radial intensity patterns within the optical fiber under the current conditions. Therefore, comparing the far-field patterns between as-drawn single crystal sapphire optical fiber (SCSF) and bundled “windmill” single crystal sapphire optical fiber (SCSF) will provide the visual
evidence in mode volume change without counting the number of modes propagating in the optical fiber.

The far-field projections of the multimode fibers have a radial intensity pattern with a speckled appearance due to the interference and superposition of many modes. Such a speckled pattern was the projected radial intensity pattern of all propagating modes under the given conditions. Generally, the total concentration of speckles decreases with decreasing number of modes propagating in the optical fiber. This phenomenon comes from the constructive and destructive interference of modes of the same phase. When the mode volume was reduced, there were fewer modes present to interfere with one another and the speckle patterns were reduced in the far-field projections. Eventually, mode volume could be reduced to a situation that such interferences would cease and only low-order modes pattern would be recognized.

The goal of far-field projection measurement was to prove the mode volume reduction in the bundled “windmill” single crystal sapphire optical fiber (SCSF). The light can be coupled from a standard multimode silica fiber in to the bundled “windmill” single crystal sapphire optical fiber (SCSF) by a single-wavelength light source. The fundamental mode and higher-order modes will be excited in the initial, however, part of the higher-order modes will be stripped out leaving other modes stabilized and propagating in the fiber. The schematic drawing of the far-field projection measurement was given in Figure 46.

In this work, lasers with 532nm, 780nm and 980nm wavelength was used in the measurement to obtain the far-field patterns. The laser beam coupled into the bundled “windmill” single crystal sapphire optical fiber (SCSF)’s by a Corning® InfiniCor 600 50/125 graded-index multimode lead-in fiber. A XYZ linear stage was used to adjust the fiber’s position before the beam profiler. The data of the far-field intensity was collected by a THORLABS
camera beam profiler (BC106-VIS) and then was sent to a computer for further analysis. The 2D far-filed projection of the tested fiber was measured and the beam width was calculated by THORLABS Beam 6.0 software. Seven measurements were made under each wavelength to provide statistical relevance.

All the components used in this measurement were fixed on an optical table.

![Diagram](image)

**Figure 46.** Schematic drawing of the far-field projection measurement.

4.2.2. Numerical Aperture Measurement

Numerical Aperture (NA) has a great importance on the mode volume prediction. Theoretical equations for NA, V parameter and number of modes (M) were given in Eq. 1, Eq. 7 and Eq. 8 respectively. Since these equations do not consider the attenuation and other factors, measurement of NA for the bundled “windmill” single crystal sapphire optical fiber (SCSF) was necessary and important for accurate prediction of the optical properties.

While the theoretical calculations for NA of weakly guiding fiber was typically accurate, a meaningless value was produced when a large refractive index difference between the core and the cladding (for example, air-clad single crystal sapphire optical fiber (SCSF)). NA around 1.4 was predicted for air-clad sapphire over the visible wavelength range, however, NA value greater than 1 means that rays incident on the end face of an optical fiber from all directions will be
guided independent of the launch angle, and that was impossible. In reality, single crystal sapphire optical fiber (SCSF) has an approximately rounded hexagonal cross sectional shape and its surface was not perfectly smooth. Furthermore, the bulk defects and defects that were adsorbed onto the fiber surface scatter the input signal into larger angle, highly lossy modes[3]. Besides, NA represents the sine of the maximum accept angle in an optical fiber, and the inverse sine of values greater than 1 were mathematically undefined. Therefore, a more accurate NA of the single crystal sapphire optical fiber (SCSF) and bundled “windmill” single crystal sapphire optical fiber (SCSF) needs to be measured from the experimental procedure.

A simple and effective way to measure the NA has the same apparatus and set up in the far-field projection measurement in section 4.2.1. Figure 47 shows the schematic drawing of NA measurement and calculation method used in this work. The fiber overfilling with injected light and then the divergence angle of the exiting beam will be measured. This was done by scanning a single-point photodetector linearly at the end-face of the tested fiber and directly measuring the beam width using a beam profiler at some distance A from the fiber’s end-face and repeating the measurement again at another distance B. The known difference between A and B (ΔL) and corresponding difference in measured beam width at each distance (Δd) results in a measured angle of divergence (θ) from which the NA would be calculated. This method defines the beam width cutoff at 5% lower intensity relative to the intensity observed at the center of the beam.
Figure 47. Numerical aperture measurement and calculation.

\[ \Delta L = \text{Position A} - \text{Position B} \]

\[ \Delta d = \frac{d_B - d_A}{2} \]

\[ \tan \theta = \frac{\Delta d}{\Delta L} \]

\[ \theta = (\tan^{-1} \frac{\Delta d}{\Delta L}) \]

\[ NA = \sin \theta = \sin (\tan^{-1} \frac{\Delta d}{\Delta L}) \]
5. Numerical Modeling and Fabrication on the Bundled “Windmill” SCSF

With consideration of cost and lead-time, the diameter and the length of the commercial single crystal sapphire optical fiber (SCSF) was chosen at 325μm and 3 inches respectively. The parameters were chosen based on the bundled “windmill” single crystal sapphire optical fiber (SCSF) given by Section 3.3. In the simulation, the wavelength was chosen at 532nm (Figure 48), 780nm (Figure 49) and 980nm (Figure 50), D1=325μm, D2=113.5μm, searching at 100 modes near the refractive index of sapphire (1.7717).

5.1. Numerical Modeling on Electric Field Distribution

The electric field distribution of bundled “windmill” single crystal sapphire optical fiber (SCSF) with different stacking layers on fundamental mode (FM) and the higher-order modes (HOMs) were demonstrated in Figure 48, Figure 49 and Figure 50. The modes in the simulated structures also can be divided into two categories: fundamental mode: $LP_{01}$ mode (Figure 48 (a), Figure 49 (a) and Figure 50 (a)) and high order modes (in the alphabetic order): $LP_{11}$, $LP_{21}$, $LP_{02}$ and $LP_{31}$ mode (Figure 48 (b-e), Figure 49 (b-e) and Figure 50 (b-e)). After simulated 100 modes in the studied structure, only the fundamental mode (FM) and four higher-order modes (HOMs) confined in the fiber’s core region. Thus, based on the results, the bundled “windmill” single crystal sapphire optical fiber (SCSF) with 325μm core diameter would be a good candidate to demonstrate the mode volume reduction in the bundled “windmill” single crystal sapphire optical fiber (SCSF).
Figure 48. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 1 layers bundled “windmill” SCSF with 325μm diameter at 532nm wavelength.
Figure 49. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 1 layers bundled “windmill” SCSF with 325μm diameter at 780nm wavelength.
Figure 50. Electric field distribution of fundamental mode (FM) (a) and higher-order modes (HOMs) (b-e) of the 1 layers bundled “windmill” SCSF with 325μm diameter at 980nm wavelength.
5.2. Fabrication

Fabrication of the first bundled “windmill” single crystal sapphire optical fiber (SCSF) began with one commercial single crystal sapphire optical fiber (SCSF) and twelve single crystal sapphire optical fiber (SCSF) grown by the Laser-heated Pedestal Growth (LHPG) system as discussed in section 4. Sapphire fiber Growth was performed at a fixed pulling rate at 50μm/s in air by using around 20 watts of applied laser power for the chosen feed and seed rods. Several pieces of fiber were produced over 8” length. The fiber grown was optically clear to the naked eye and under optical microscope examination. One such fiber with diameter around 115μm is shown in Figure 51 under macroscopic and Figure 52 under optical microscope. With a diameter set point of 115μm, the diameter variation in this fiber is about 1.7%. Based on previous study[49], this level of variation indicated the good fiber growth capability of our Laser-heated Pedestal Growth (LHPG) system.

![Figure 51](image1.jpg)

**Figure 51.** Picture of as grown 115μm diameter sapphire fiber.

![Figure 52](image2.jpg)

**Figure 52.** As grown sapphire fiber with diameter of 115μm under optical microscope.
These fibers were cleaved into pieces approximately 3 inch each, and then cleaned by ethanol and distilled water. The fibers were assembled in the pattern given in Figure 33, which consisted of a central single crystal sapphire optical fiber (SCSF) as the core surrounded by twelve pulled single crystal sapphire optical fiber (SCSF) as the cladding. The fibers were held in place by using platinum wire. The platinum wire was wound around the fibers to preserve the ordered arrangement of the bundle and was wound around the bundle in several locations across the entire length of the bundle. An image of the polished 1-layer bundled “windmill” single crystal sapphire optical fiber (SCSF) under optical microscope can be seen in Figure 53 (5X magnification) and Figure 54 (10X magnification). The background in this image was the phenyl salicylate wax, which used to hold the bundle during the polish process.

Figure 53. 5X magnification of bundled “windmill” SCSF with a core diameter of 325μm.
Figure 54. 10X magnification of bundled “windmill” SCSF with a core diameter of 325μm.
6. Conclusion

The modal characteristics and confinement losses of the fundamental mode were analyzed via the finite element method by varying the effective core diameter and the dimensions of the “windmill” shaped cladding. The Finite Element Method (FEM) simulation results showed that the number of guided modes were significantly reduced in the “windmill” fiber design, as the radial dimension of the air and single crystal sapphire optical fiber (SCSF) cladding regions increase with a corresponding decrease in the azimuthal dimension. Furthermore, a “windmill” single crystal sapphire optical fiber (SCSF) design with a single-mode operation in the spectral range from 0.4μm to 2μm was proposed. The fiber design analyzed by Finite Element Method (FEM) simulations demonstrated a significant difference in the confinement loss between the first two modes which ensured single-mode operation with an effective core diameter as large as 14μm. The high leakage losses of the higher-order mode (HOM) in the studied fibers were reflected in their distribution in the electric field contour plots. Such a fiber was expected to improve the performance of many of the current sapphire fiber optic sensor structures.

The first bundled “windmill” single crystal sapphire optical fiber (SCSF) has been modeled and fabricated as an alternate of “windmill” single crystal sapphire optical fiber (SCSF). The bundled “windmill” single crystal sapphire optical fiber (SCSF) has been fabricated by using the Laser-heated Pedestal Growth (LHPG) system, which was constructed in-house by Virginia Tech.
The new contributions to the body of literature in this field of sapphire fiber optics are summarized as follows:

- The first “windmill” structure design on a single crystal sapphire fiber
- The first to use Finite Element Method (FEM) modeling for a “windmill” single crystal sapphire optical fiber (SCSF)
- Design optimization of the first “windmill” single crystal sapphire optical fiber (SCSF)
- Design optimization of the first single mode “windmill” single crystal sapphire optical fiber (SCSF)
- Design optimization of the first bundled “windmill” single crystal sapphire optical fiber (SCSF)
- Fabrication the first bundled “windmill” single crystal sapphire optical fiber (SCSF)
7. Future Work

Single crystal sapphire fiber in ultrahigh temperature applications shows lots of benefits and advantages compared with the commercially available optical fibers, and much work still needs to be done. As discussed in the previous sections, the ability to produce “windmill” single crystal sapphire optical fiber (SCSF) is still a big challenge from fabrication standpoint. There are two possible methods to achieve that: chemical etching and physical removal. Chemical etching could be implemented by masking the “windmill” portion and etching the unwanted sections. CO₂ laser direct heating could be a possible solution as a physical removal process to produce a “windmill” single crystal sapphire optical fiber (SCSF). Depending on the scale size of the single crystal sapphire fiber, beam diameter and power output of the chosen laser could be very critical parameters to have a successful fabrication.

Future works from the modeling perspective could include finding the optimized “windmill” single crystal sapphire optical fiber (SCSF) structure depending on the material source. To have the precise optimized “windmill” single crystal sapphire optical fiber (SCSF) design on selected single crystal source, material loss as well as surface roughness should be introduced into the simulation. Future works from the fabrication perspective could include the optical characterization of a bundled “windmill” single crystal sapphire optical fiber (SCSF) and a conventional single crystal sapphire optical fiber (SCSF), as well as the comparison between the measurements and numerical modeling.


Appendices

A. Function block in the Parker Linear stages control system
B. Global variables in the Parker Linear stages control system

The following code used to define the variables in the Parker Linear stages control system, which used to control the pulling system in this work.

```
VAR_GLOBAL
  CounterPLC: DINT := 0;
  g_PosDistance: REAL := 200.0;
  g_NegDistance: REAL := -200.0;
  g_Vel: REAL := 25;
  g_Acc: REAL := 100.0;
  In_Power: BOOL;
  In_Reset: BOOL;
  In_Pos: BOOL;
  In_Neg: BOOL;
  In_Stop: BOOL;
  In_Zero: BOOL;
  g_MoveDwellPos: BOOL := FALSE;
  g_MoveDwellNeg: BOOL := FALSE;
  g_MoveDwellPos_X: BOOL := FALSE;
  g_MoveDwellNeg_X: BOOL := FALSE;
  g_MoveDwellPos_Y: BOOL := FALSE;
  g_MoveDwellNeg_Y: BOOL := FALSE;
  g_MoveDwellPos_Z: BOOL := FALSE;
  g_MoveDwellNeg_Z: BOOL := FALSE;
  g_MoveDwellPos_A: BOOL := FALSE;
  g_MoveDwellNeg_A: BOOL := FALSE;
  g_GotSDO.POSitionPos: BOOL;
  g_GotSDO.VelocityPos: BOOL;
  g_GotSDO.POSitionNeg: BOOL;
  g_GotSDO.VelocityNeg: BOOL;
  g_GotSDO.Y.POSitionPos: BOOL;
  g_GotSDO.Y.POSitionNeg: BOOL;
  DC_InSync: BOOL;
  g_FirstSync: BOOL;
  g_LostSync: BOOL;
  CountX: DINT;
END_VAR
```
C. Parker Linear Stages’ code

The following code was input to Parker Automation Control (PAC) system and used to control the Parker Linear stages to pull fibers. Half of the code is given by the Parker company, and my contribution to the coding work including add new variables, add the logic code to the new variables, test the code and debug.

AxisVar := X;

(* IF iStatus > 1 AND NOT(DC_InSync) THEN
   Got_DC_OutOfSync := TRUE;
END_IF *)

CASE iStatus OF

0: //Wait Time

IF EtherCAT_Master.xConfigFinished (*AND DC_InSync*) THEN
   iStatus:=iStatus + 1;
END_IF

1: //Wait Time

(* AxisControl(Axis:=X, Enable:=TRUE);
IF DC_InSync THEN
   iStatus:=iStatus + 1;
END_IF *)

// 2: Wait for Drive to be ready

AxisControl(Axis:=X, Enable:=TRUE);
In_Power:=TRUE;
IF AxisControl.Ready AND X.nAxisState=standstill THEN
   iStatus:=iStatus + 2;
END_IF;

3: //Go Home
Go_Home(Axis:= X, Execute:= TRUE, Position:= 0, Done=> , Busy=> , CommandAborted=> , Error=> , ErrorID=> );
iStatus:=iStatus + 1;

4: //Wait for Home to Finish

Go_Home(Axis:= X, Execute:= TRUE, Position:= 0, Done=> , Busy=> , CommandAborted=> , Error=> , ErrorID=> );
IF Go_Home.Done AND X.dwActPosition=0 THEN
   Go_Home.Execute:=FALSE;
   DoMove(Axis:=X, Execute:= FALSE);
iStatus:=iStatus + 1;
END_IF

5: //Start positive move
DoMove(Axis:=X, Distance:= g_PosDistance, Velocity:=g_Vel, Acceleration:=g_Acc, Deceleration:=g_Acc, Execute:= TRUE);
IF DoMove.Busy THEN
iStatus := iStatus + 1;
END_IF

6: // Wait for Move Finish
DoMove(Axis:=X, Distance:= g_PosDistance, Velocity:=g_Vel, Acceleration:=g_Acc, Deceleration:=g_Acc, Execute:= TRUE);
IF DoMove.Done AND X.nAxisState=standstill THEN
    DoMove(Axis:=X, Execute:= FALSE);
    iStatus := iStatus + 1;
END_IF

7: // Wait Time
    g_MoveDwellPos := TRUE;
    TimerON(PT:=tWait, IN:=TRUE);
    IF TimerON.Q=TRUE THEN
        TimerON(IN:=FALSE,PT:=T#0S);
        iStatus := iStatus + 1;
        g_MoveDwellPos := FALSE;
    END_IF

8: // Start positive move
    DoMove(Axis:=X, Distance:= g_NegDistance, Velocity:=g_Vel, Acceleration:=g_Acc, Deceleration:=g_Acc, Execute:= TRUE);
    IF DoMove.Busy THEN
        iStatus := iStatus + 1;
    END_IF

9: // Wait for Move Finish
    DoMove(Axis:=X, Distance:= g_NegDistance, Velocity:=g_Vel, Acceleration:=g_Acc, Deceleration:=g_Acc, Execute:= TRUE);
    IF DoMove.Done AND X.nAxisState=standstill THEN
        DoMove(Axis:=X, Execute:= FALSE);
        CountX := CountX + 1;
        iStatus := iStatus + 1;
    END_IF

10: // Wait Time
    g_MoveDwellNeg := TRUE;
    TimerON(PT:=tWait, IN:=TRUE);
    IF TimerON.Q=TRUE THEN
        TimerON(IN:=FALSE,PT:=T#0S);
        iStatus := 5;
        g_MoveDwellNeg := FALSE;
    END_IF

END_CASE;

=====================================================================
===
AxisVar := Y;

(* IF iStatus > 1 AND NOT(DC_InSync) THEN
    Got_DC_OutOfSync := TRUE;
END_IF *)
CASE iStatus OF

0: //Wait Time

IF EtherCAT_Master.xConfigFinished (*AND DC_InSync*) THEN
   iStatus:=iStatus + 1;
END_IF

1: //Wait Time
   (* AxisControl(Axis:=X, Enable:=TRUE);
   IF DC_InSync THEN
      iStatus:=iStatus + 1;
   END_IF *)

   // 2: Wait for Drive to be ready

   AxisControl(Axis:=Y, Enable:=TRUE);
   In_Power:=TRUE;
   IF AxisControl.Ready AND Y.nAxisState=standstill THEN
      iStatus:=iStatus + 2;
   END_IF;

3: //Go Home
   Go_Home(Axis:= Y, Execute:= TRUE, Position:= 0, Done=> , Busy=> , CommandAborted=> , Error=> , ErrorID=> );
   iStatus:=iStatus + 1;

4: //Wait for Home to Finish

   Go_Home(Axis:= Y, Execute:= TRUE, Position:= 0, Done=> , Busy=> , CommandAborted=> , Error=> , ErrorID=> );
   IF Go_Home.Done AND Y.dwActPosition=0 THEN
      Go_Home.Execute:=FALSE;
      DoMove(Axis:=Y, Execute:= FALSE);
      iStatus:=iStatus + 1;
   END_IF

5: //Start positive move
   DoMove(Axis:=Y, Distance:= g_PosDistance, Velocity:=g_Vel, Acceleration:=g_Acc, Deceleration:=g_Acc, Execute:= TRUE);
   IF DoMove.Busy THEN
      iStatus:=iStatus + 1;
   END_IF

6: // Wait for Move Finish
   DoMove(Axis:=Y, Distance:= g_PosDistance, Velocity:=g_Vel, Acceleration:=g_Acc, Deceleration:=g_Acc, Execute:= TRUE);
   IF DoMove.Done AND Y.nAxisState=standstill THEN
      DoMove(Axis:=Y, Execute:= FALSE);
      iStatus:=iStatus + 1;
   END_IF

7: //Wait Time
   g_MoveDwellPos := TRUE;
   TimerON(PT:=tWait, IN:=TRUE);
   IF TimerON.Q=TRUE THEN
      TimerON(IN:=FALSE,PT:=T#0S);
      iStatus:=iStatus + 1;
g_MoveDwellPos := FALSE;
END_IF

8: // Start positive move
DoMove(Axis:=Y, Distance:= g_NegDistance, Velocity:=g_Vel, Acceleration:=g_Acc,
Deceleration:=g_Acc, Execute:= TRUE);
IF DoMove.Busy THEN
  iStatus:=iStatus + 1;
END_IF

9: // Wait for Move Finish
DoMove(Axis:=Y, Distance:= g_NegDistance, Velocity:=g_Vel, Acceleration:=g_Acc,
Deceleration:=g_Acc, Execute:= TRUE);
IF DoMove.Done AND Y.nAxisState=standstill THEN
  DoMove(Axis:=Y, Execute:= FALSE);
  CountX := CountX + 1;
  iStatus:=iStatus + 1;
END_IF

10: // Wait Time
  g_MoveDwellNeg := TRUE;
  TimerON(PT:=tWait, IN:=TRUE);
  IF TimerON.Q=TRUE THEN
    TimerON(IN:=FALSE,PT:=T#0S);
    iStatus:=5;
    g_MoveDwellNeg := FALSE;
  END_IF

END_CASE;