AFRL-AFOSR-VA-TR-2022-0211

# Development of Anti-Resonant Hollow Core Fiber for High Power and Mid-wave Infrared Transmissions

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**06/03/2022**
**Final Technical Report**



Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia 22203
Air Force Materiel Command

# REPORT DOCUMENTATION PAGE

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.**

| **1. REPORT DATE** | **2. REPORT TYPE** | **3. DATES COVERED** | |
|---|---|---|---|
| 20220603 | Final | **START DATE** 20181201 | **END DATE** 20220228 |

**4. TITLE AND SUBTITLE**
Development of Anti-Resonant Hollow Core Fiber for High Power and Mid-wave Infrared Transmissions

| **5a. CONTRACT NUMBER** | **5b. GRANT NUMBER** | **5c. PROGRAM ELEMENT NUMBER** |
|---|---|---|
| | FA9550-19-1-0049 | 61102F |
| **5d. PROJECT NUMBER** | **5e. TASK NUMBER** | **5f. WORK UNIT NUMBER** |

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PENNSYLVANIA STATE UNIVERSITY
201 OLD MAIN
UNIVERSITY PARK, PA
US

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Air Force Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

**10. SPONSOR/MONITOR'S ACRONYM(S)**
AFRL/AFOSR RTB1

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
AFRL-AFOSR-VA-TR-2022-0211

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
A Distribution Unlimited: PB Public Release

**13. SUPPLEMENTARY NOTES**


**14. ABSTRACT**
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**15. SUBJECT TERMS**

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** |
|---|---|---|---|---|
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | UU | 40 |
| U | U | U | | |

| **19a. NAME OF RESPONSIBLE PERSON** | **19b. PHONE NUMBER** *(Include area code)* |
|---|---|
| JOHN LUGINSLAND | 000-0000 |

**Standard Form 298** (Rev.5/2020)
Prescribed by ANSI Std. Z39.18

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# Development of Anti-Resonant Hollow Core Fiber for High Power and Mid-wave Infrared Transmission

FA9550-19-1-0049
Final Report

Reporting Period: 12/01/2018 – 02/28/2022

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# Abstract

A thorough investigation into the design of anti-resonant hollow core fiber (ARHCF) has been performed. Using Comsol Multiphysics, each design parameter was studied for how it affected the guidance and loss of the modes of the fiber. This understanding was used to optimize two designs of fiber, one for low loss around 1 μm for high power laser delivery, and the other for broadband transmission in the mid-infrared.

The two fiber designs were drawn at UCF, and delivered to the Penn State Applied Research Lab, Electro-Optics Center (ARL EOC). A high power testing setup was developed, based on a single mode, 1 kW 1060 nm CW laser. The ARHCF was tested, and powers up to 170 W were able to be coupled into the fiber. Heating at the fiber facet limited the total power able to be coupled into the fiber. Future efforts in high power delivery testing will incorporate end caps in order to mitigate facet heating and improve coupling efficiencies.

The mid-infrared fiber was tested with a broadband source, as well as two quantum cascade lasers. We have shown a silica-based ARHCF with guidance up to 4.6 μm with relatively low loss, which is a significant improvement over previously published work. This shows that silica-based ARHCF can be a viable option for MWIR transmission in the 3-5 μm region, an important atmospheric window for applications such as infrared counter measures and remote sensing.

# Technical Highlights

## Introduction

Applications such as directed energy (DE) and infrared countermeasures (IRCM) require optical transmission systems capable of transmitting high power laser light from the source to the target in an efficient and flexible manner. Optical fiber is limited in both the maximum power, as well as range of wavelengths, that can be transmitted with low loss.

Currently, the power handling capability of optical fibers is primarily limited by glass damage thresholds and induced nonlinearities. Delivery fibers for high power laser systems are drastically limited in length due to the onset of stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). A common approach to these issues is to make the core of the fiber larger, as this lessens the intensity of light in the fiber core. In order to mitigate unwanted nonlinear effects, a majority of high power delivery fibers have increased core sizes, which are generally used near the threshold of multimode operation. Under high power, thermal changes lead to transverse mode instabilities (TMI), random fluctuations in the mode within the core, which degrade the overall beam quality.

To overcome these degenerative effects, significant research is going into the development of solid optical fibers with higher thresholds for nonlinearities. While improvements in mode stability and nonlinear effect suppression have been made, delivery fibers are still limited in usable length when used for very high powers.

An alternative to solid glass fiber for high power applications is hollow core fiber. For example, a 10 meter long fiber with a 40 µm core will induce the onset of SBS at a power of 50 W, whereas, for a similar fiber with a hollow core, the SBS threshold would be around 10 MW [1]. This increase is caused by the very small overlap of the laser light with glass in these fibers.

As total internal reflection no longer applies, there are several mechanisms for guiding light in an air core. Recently, HCFs based on the anti-resonant effect (ARHCF) have been quickly gaining attention for their excellent guiding properties, such as low loss, large core sizes, and wider transmission windows than hollow photonic bandgap fibers [2].

Anti-resonant HCFs have significantly simpler designs compared to other microstructured fibers, namely photonic bandgap fibers, which leads to more flexibility and less complex fabrication.

## Project Plan

The plan is to investigate ARHCF for its use in both high power delivery and mid-wave infrared (MWIR) delivery. Two different fiber designs will be developed and optimized using Comsol Multiphysics. The high power delivery fiber will be designed for 1 µm transmission, and the MWIR fiber will be design for 3-5 µm transmission. The designs will then be fabricated by the

University of Central Florida using the stack and draw method, their fiber draw tower, and their expertise in drawing microstructured fiber. After fabrication, the fibers will be characterized for their performance in their respective application areas at the Penn State Applied Research Lab, Electro-Optics Center (PSU ARL EOC). The key parameters that will be analyzed are propagation loss, bending loss, and mode quality at the wavelengths of interest. In addition, the high power delivery fiber will be tested under high input power conditions for understanding of optimized coupling conditions and the power handling ability of the fiber. The performance of the two fibers and their potential in the proposed applications will then be compared to commercial and state of the art fibers that are currently available. The proposed work has been divided into the following tasks:

- Task 1 - Design of ARHCF for High Power 1 µm Delivery
- Task 2 – High power delivery fiber fabrication and characterization
- Task 3 – High power testing
- Task 4 - Mid-Infrared Fiber Design and Testing

## Task 1 - Design of ARHCF for High Power 1 µm Delivery

The first focus was on designing an ARHCF for delivery of high power laser light around 1064 nm, where many laser weapons systems currently operate. There are several key design parameters of ARHCF that affect its performance. In order to have a good delivery fiber, it needs to be low loss at the wavelength of choice, have good bending performance, and have low overlap of the light with the glass of the fiber structure. Low propagation and bending loss are obviously important for having an efficient delivery system and for not causing excessive heating from any leakage loss. As previously mentioned, the overlap of the light with the glass is important for controlling nonlinear effects, because as you decrease the amount of light in the glass of the fiber, the increase the thresholds of the nonlinear effects.

A commercial finite element software, Comsol Multiphysics, was used for the design and optimization of the fiber. In Comsol, the geometrical design of the fiber is constructed, the size of the mesh is determined, and the appropriate materials are applied to the geometry. The desired physics is then selected and studies can be setup for a variety of calculations.For the geometry of the ARHCF, each element is defined as a variable, so it can later be scanned and its effect on the fiber performance can be analyzed. An example of an ARHCF design is shown in Fig. 1. The design element variables are wavelength, capillary thickness (t), capillary radius ($R_c$), inner radius of the jacketing tube ($R_{it}$), outer radius of the jacketing tube ($R_{ot}$), and the fiber radius of curvature (RC).

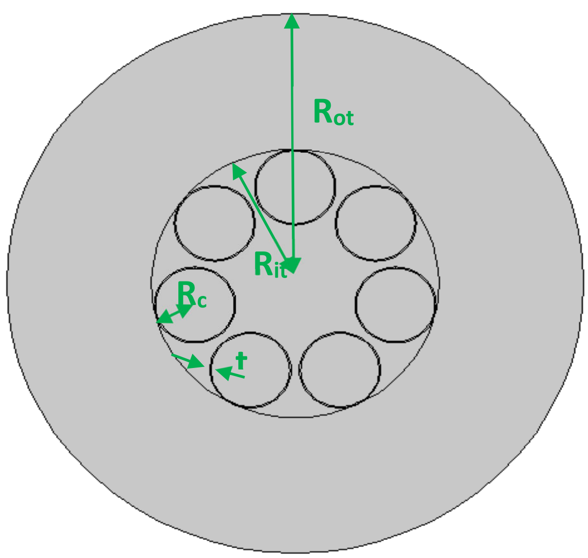



Fig. 1. Geometry of Anti-Resonant Hollow Core Fiber

*Determining mesh size*

An important element to the accuracy of the model is its mesh. The mesh size determines the resolution of the calculations. Because this particular fiber design contains both large (100's µm) and very small (100's nm) elements, an adaptable mesh is crucial to achieve an accurate calculation. The mesh size must also take into consideration the wavelength of the light.

A group at the University of Southampton, Poletti et al., determined that the maximum element size in the glass should be 1/6 of the wavelength of light [3]. For 1064 nm, this corresponds to a value of 0.18 µm.

The mesh for this fiber was defined separately for the air core and for the glass elements. The maximum element size of the mesh in the glass elements was scaled down from 0.35 µm to 0.075 µm as the change in the loss of the fundamental mode, as well as the shape of the loss spectrum, was observed. It was noted that as the maximum element size deceased, the fundamental mode loss decreased, then appeared to fluctuate around a fairly stable value once

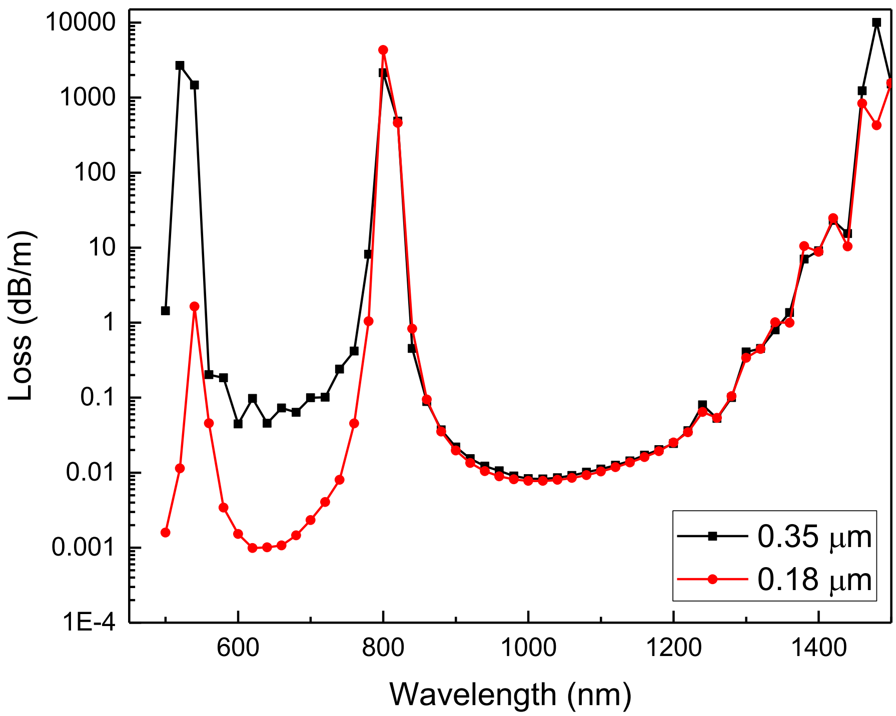



Fig. 2. Comparison of different mesh sizes on loss spectra.

the element size went below 0.2 µm, which agrees with the determined value from Poletti. A comparison of the loss spectrum calculated with a maximum element size of 0.35 vs 0.18 µm is shown in Fig. 2. Clearly at lower wavelengths, there is a much greater discrepancy between the calculated values and the spectrum is less smooth.

In order to further verify the accuracy of our model and our mesh, the exact fiber geometry used in Ref. 2 was recreated in our Comsol model with our maximum mesh element size in the glass set to 0.18 µm. The maximum element size in the air was set to 0.27 µm (or λ/4) also as per Poletti et al. The calculated loss values from our Comsol simulation were nearly identical to those of Ref. 3, but the calculation times were extremely long. In order to lessen this, the maximum element size in the air core was increased to 1 µm, where the loss values still matched those of Poletti, but the calculation times were less burdensome.

The final mesh is shown in Fig. 3. This study gave confirmation that our mesh was defined well and that any future calculations would be accurate.

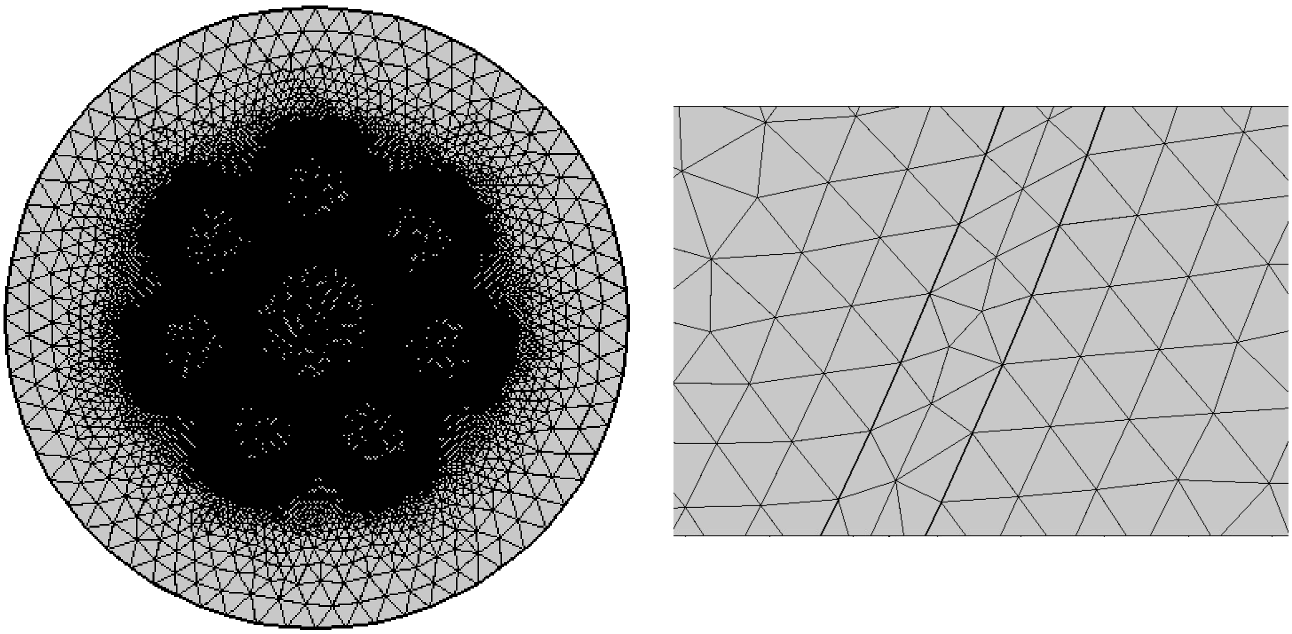


Fig. 3. Image of final mesh, with a zoom in on one of the capillary edges.

*Determining capillary thickness*

One of the simplest, but most crucial, elements of the fiber geometry to determine is the thickness of the capillaries. This thickness determines the resonance that gives the "anti-resonant" fiber its name. For wavelengths that are resonant with the capillary thickness, the light will be coupled into the capillaries and then leaked out of the fiber through the cladding. There will be no transmission at these wavelengths. An example of resonant light coupling into an ARHCF's capillaries is shown in Fig. 4.

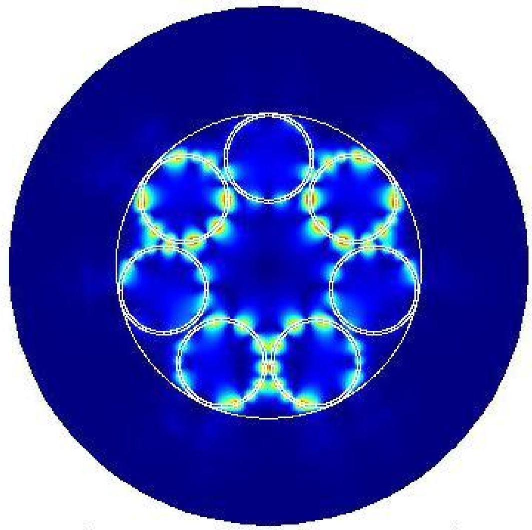


Fig. 4. Image of light coupling to the capillaries.

For all other non-resonant (or anti-resonant) wavelengths, the light will be confined to the core and will propagate. To determine the resonant wavelengths, the following equation is used:

$$\lambda_m = \frac{2t}{m}\sqrt{n^2 - 1} \qquad (m = 1,2,3 \ldots)$$

Here, $\lambda_m$ is the resonance wavelength, $t$ is the thickness of the silica, $m$ is the order of the resonance, and $n$ is the index of refraction of the silica. Figure 5 shows a scan of thicknesses for a fixed wavelength of 1064 nm, with two resonances at thicknesses of 550 μm and 1050 μm.

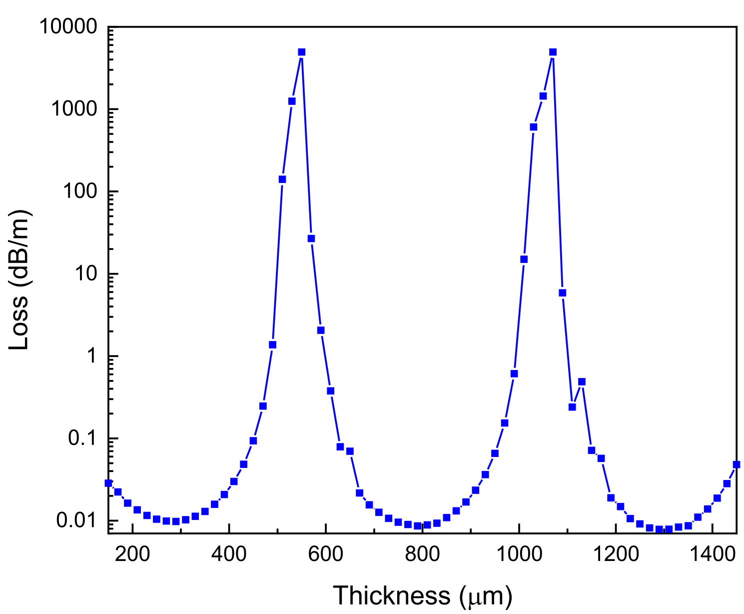



Fig. 5. Loss vs. thickness showing multiple resonances.

Generally, the lowest propagation loss would be achieved by selecting a capillary thickness that is near-centered between two resonant values for the wavelength at which you will be operating. In addition to these calculations however, the influence of the fiber fabrication process must also be taken into consideration.

For example, for a wavelength at 1064 nm, the halfway point between the first and second resonance thickness would be 760 nm. Using Comsol, it was found that there was a very close local minimum propagation loss at 790 nm. This is shown in Fig. 6 below.

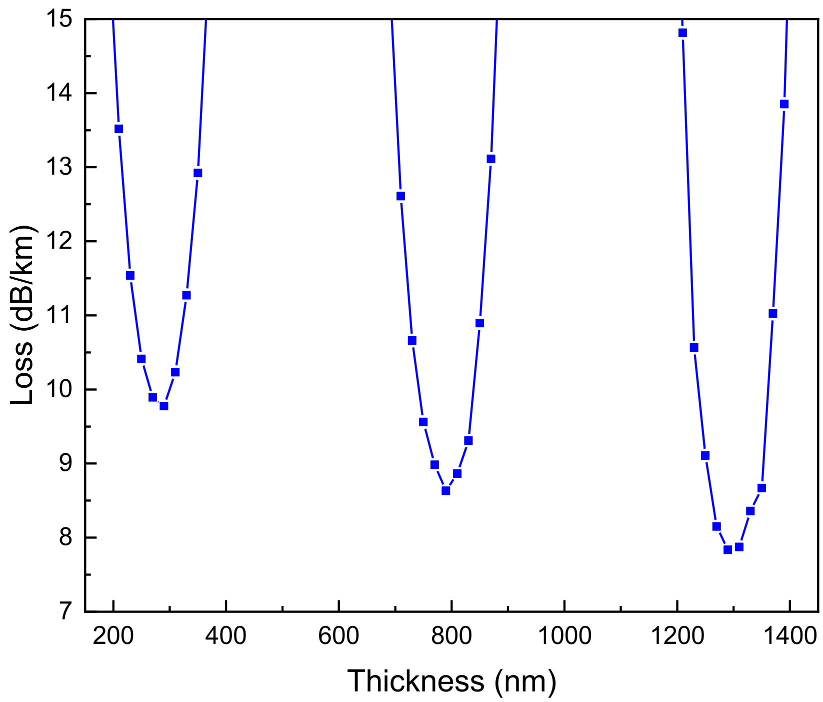



Fig. 6. Loss vs, thickness for 1064 nm.

Figure 6 shows lowest possible propagation loss at a thickness value of about 1.3 µm; however, when discussing possible designs with the fiber fabrication scientist, it was suggested that better performance was achieved with thinner capillaries. Figure 6 shows that a thickness value of 250 nm produces only a marginally higher calculated loss (8 to 10 dB/km), but it's predicted to perform much better in fabrication by the fabrication scientist. This may be because the thinner capillaries lead to a smoother outer surface, which would mean less surface roughness for the core boundary.

Using the local propagation loss minima calculated through Comsol and a knowledge of fabrication performance, a goal capillary thickness of 200-250 nm was selected.

*Optimizing single-modedness*

Another important design consideration is the mode content of the fiber. ARHCFs are not strictly single-moded, as they can support many higher order modes (HOMs). Generally, these HOMs have higher propagation loss values than the fundamental mode. Because of this, after several meters of propagation, the HOMs will mostly leak out and the beam will be primarily consist of the fundamental mode.

The fundamental mode of an ARHCF looks mostly like a Gaussian beam, similar to that of a standard single mode fiber, as shown in Fig. 7. This can be referred to as an $LP_{01}$-like mode.

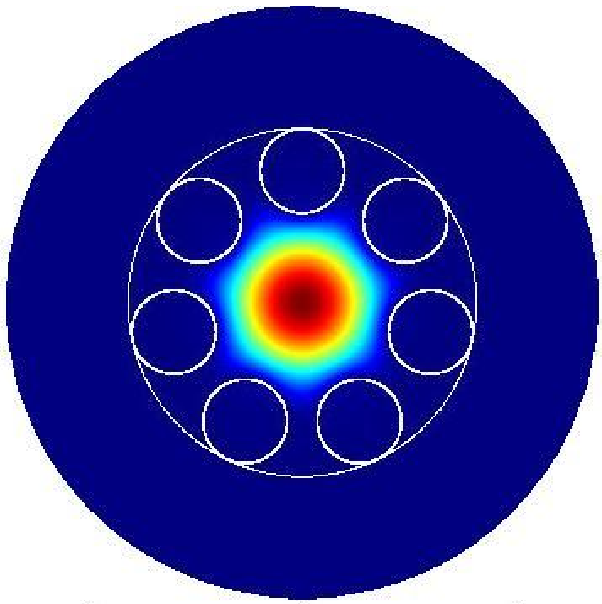


Fig. 7. Fundamental mode of an ARHCF.

Examples of some of the HOM that ARHCF can support are shown in Fig. 8 below.

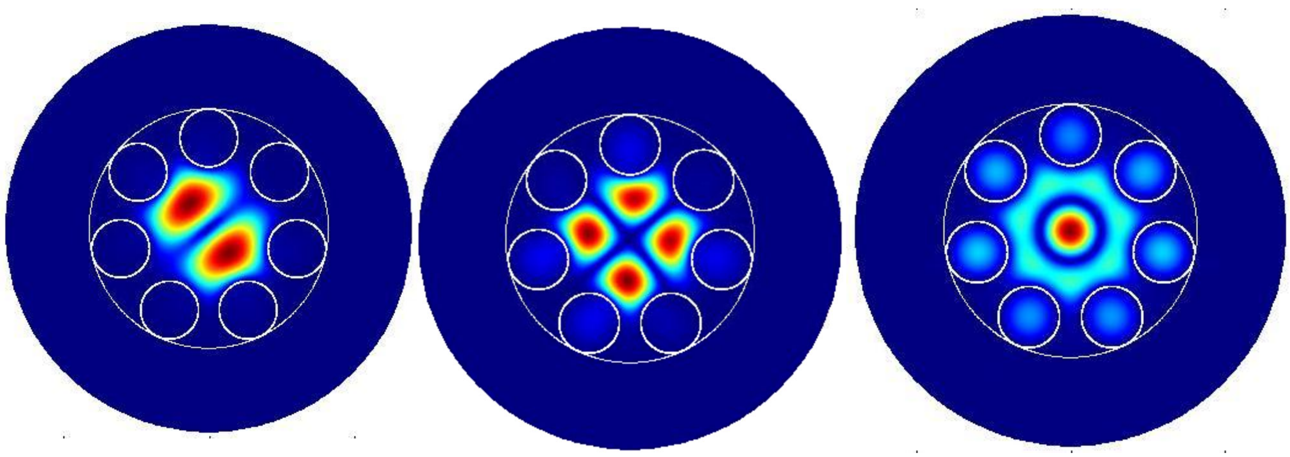


Fig. 8. Higher order modes of ARHCF.

Depending on the application of the fiber, very high single mode beam quality or very short fiber lengths may need to be used. Because if this, the loss of the HOMs needs to be well controlled.

It has been found that the most important design element for determining the HOM loss of an ARHCF is the ratio of the capillary diameter to the core diameter. The reason why this ratio is important is because it determines which modes of the core will couple into the capillaries, and therefore, out of the fiber. The capillaries support modes similar to the fiber core, as shown in Fig. 9. When the effective refractive index of the core mode matches the index of the capillary mode, the light couples between them, and the light will leak out of the fiber. If the ARHCF is properly designed, the HOMs can be selectively coupled into the capillary modes and leaked out of the core.

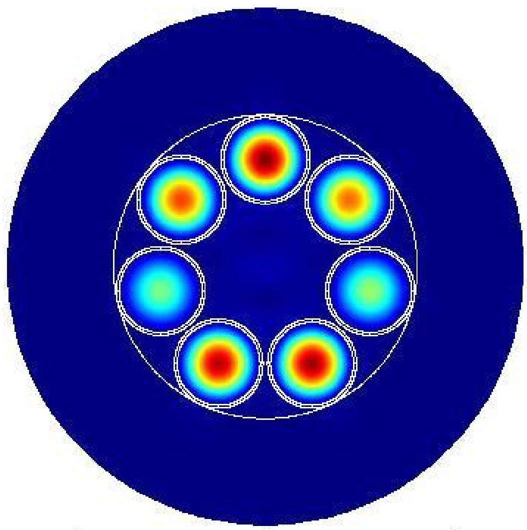


Fig. 9. Capillary mode of ARHCF.

The ratio between the loss of the fundamental mode and the loss of the first higher order mode is called the higher order mode extinction ratio (HOM ER). When designing an ARHCF to be used in single mode operation, it must have a low fundamental mode loss, as well as a high HOM ER. However, these two elements were found to be at odds with one another, as shown in Fig. 10. As the size of the core was increased through increasing the inner radius of the jacketing tube, the fundamental mode loss decreased, as did the HOM ER.

The improvement of one parameter while lessening another will also be seen in the following section.

Important to note that the last data points at an inner radius of 41.75 µm looks ideal due to the very low propagation loss and relatively high HOM ER, however, this radius value leads to a HOM loss value of only 0.7 dB/m. A HOM loss of less than 1 dB/m would not be suitable for many applications requiring a mostly single mode beam.

The careful balance of propagation loss and HOM loss lead to the selection of 41 µm for the inner jacketing tube radius, with a capillary radius of 12 µm. the lowest higher order mode loss at this value was 13.6 dB/m, while the fundamental mode propagation loss was 0.0093 dB/m, giving a HOM ER of 1462.

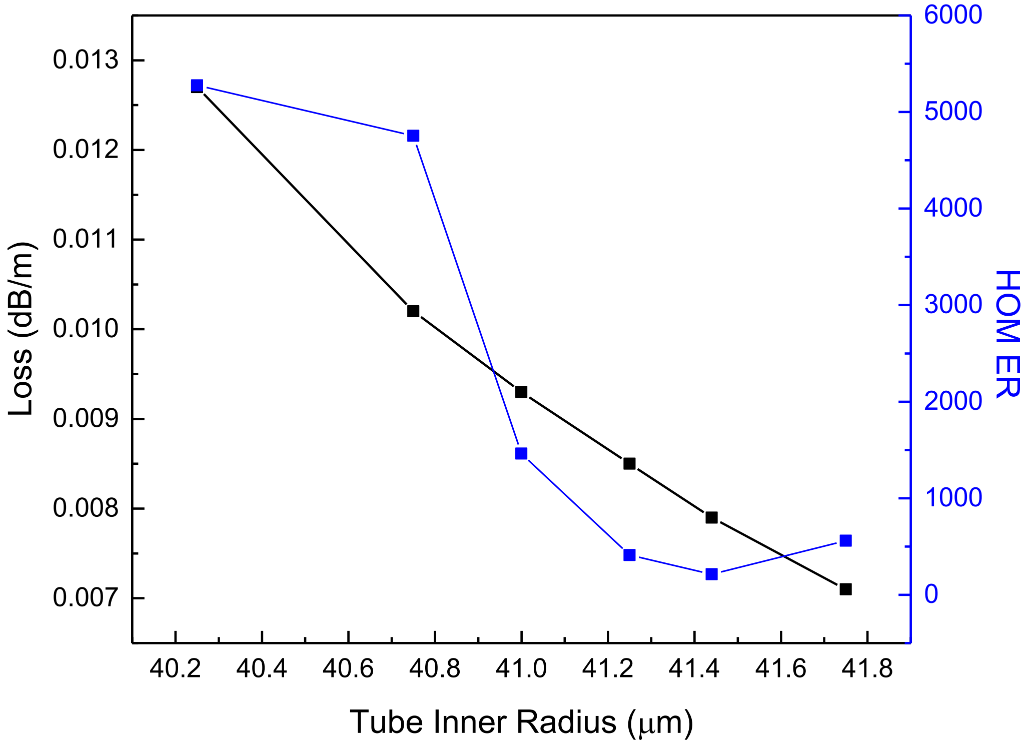



Fig. 10. Loss and higher order mode extinction ratio as a function of tuber inner radius.

*Optimizing bend loss*

Additionally, when designing an optical fiber, considering its performance under bending is important for any practical application. As a fiber is bent, the properties will change and the loss of the various modes tend to increase. How well the core modes are confined determine how much additional loss they gain as the fiber is bent. In general, as you bend an optical fiber, the core will be distorted and some of the light will begin to leak out. The tighter the bend, the higher the propagation loss.

In Comsol, a bending radius of curvature can be define and scanned, and the effect on the propagation loss observed. The plot below in Fig. 11 shows the known gradual increase in propagation loss as the bending radius decreases.

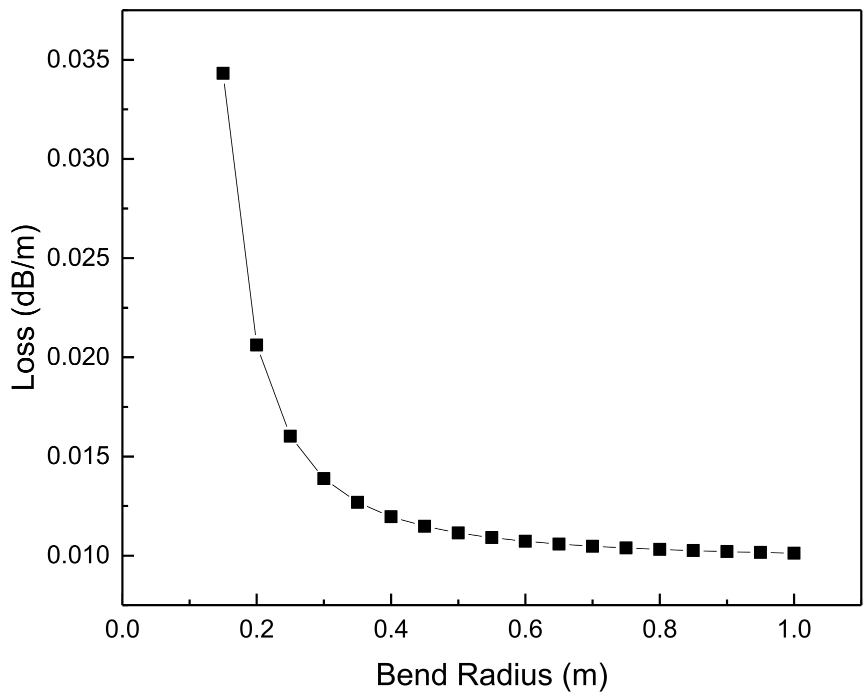



Fig. 11. Loss vs. bend radius showing a gradual increase with decreasing bend radius.

However, similarly to the last section, an additional key element to the bend loss of ARHCF is the coupling of the core modes to the modes of the capillaries. At a certain radius of curvature, the effective mode index of the now distorted fundamental mode of the core will match that of the capillary mode, and the light will couple out.

This can be seen as a large jump in propagation loss when certain radii of curvature are reached, as shown in Fig. 12 below. At a bend radius of approximately 0.55 m, all of the light from the fundamental core mode couples into one of the modes of the capillary and is lost. This coupling is shown in the mode image insert of Fig. 12. This is due to the matching of their effective refractive indices at that radius due to the bending causing distortion in the modes.

These peaks in the bending loss can be unexpected and cause major issues. As can be seen in Fig. 12, the loss can jump over 3 orders of magnitude with a very small change in bend radius.

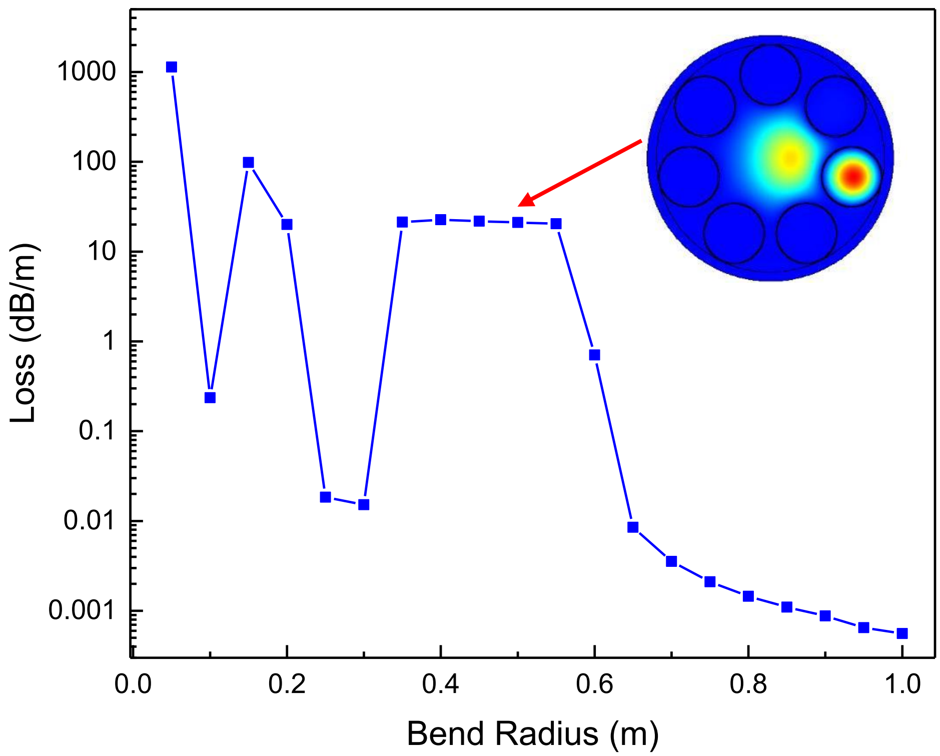



Fig. 12. Loss vs. bend radius showing coupling to capillary modes, with an inserted mode image.

The coupling of the core mode to the capillary modes as the ARHCF is bent can be controlled through controlling the core size. The previous section discussed the importance of the ratio between the core diameter and the capillary diameter for controlling the mode quality of the fiber. For this reason, that ratio was kept approximately constant while the size of the core was adjusted.

The plot below in Fig. 13 shows multiple traces with various core sizes (the numbers correspond to the capillary radius). As the size of the core decreases, the location of the loss peaks shifts to smaller bend radii, as well as get narrower. For very large core sizes, large, wide loss plateaus at large bend radii would make any practical use of the ARHCF nearly impossible.

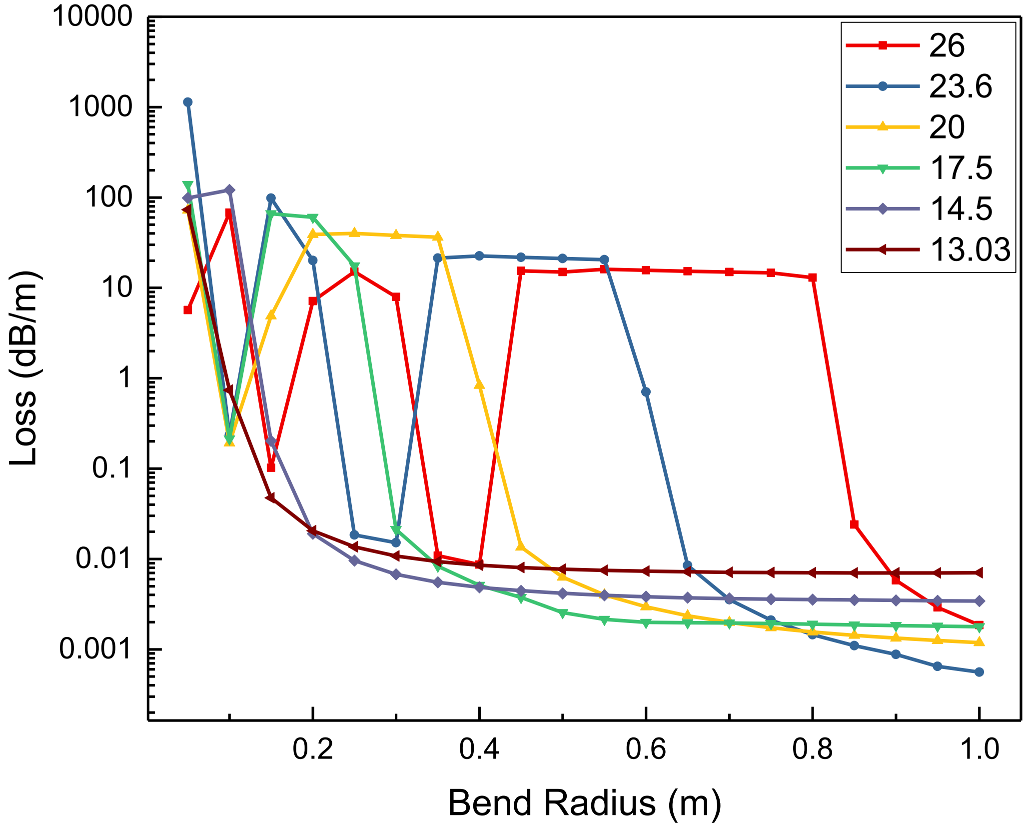



Fig. 13. Loss vs. bend radius for ARHCF with different core sizes, showing changing coupling to the capillary modes.

However, it is also important to note that as the core gets smaller, the propagation loss at large bend radii increases. This shows that cannot ignore bending when designing your ARHCF. If you were to only focus on straight propagation loss, you would select a large core size, which would lead to terrible bending loss.

As with other elements of ARHCF fiber design, there is a give and take with increasing the size of the core. As the straight propagation loss decreases, the bending performance degrades, so the application that the fiber will be used for must be carefully considered during the design.

For this application, a capillary radius of 12 μm and jacketing tube inner radius of 41 μm limited the first bending mode resonance to below a bend radius of 10 cm, which was deemed suitable.

*Jacketing Tube Thickness*

The next parameter to be discussed is the outer diameter of the jacketing tube. This parameter has very little impact on the optical performance of the ARHCF. If the outer diameter of the fiber is large, it will limit the flexibility of the fiber and its minimum bend radius, which may be an issue if your space is limited. However, if you are not limited by space and are concerned about bending loss, a thicker jacketing tube could be helpful. The jacketing tube thickness will also determine how well the ARHCF integrates with standard optical fiber. If the jacketing tube diameter is of a similar thickness to standard optical fiber (~125-140 µm), then splicing the two fibers together will be easier. These splices will be weak. This is because in order to splice an ARHCF, the temperature of the splice must be greatly reduced in order to not collapse the air holes.

In order to maintain flexibility and compatibility with standard optical fiber, an outer jacketing tube diameter of 140 µm was selected.

*Final Design*

After many calculations and a discussion with the fabrication scientist at UCF, a final design was decided upon. The parameters have already been discussed, but they will be summarized here:

Outer jacketing tube radius: 70 µm
Inner jacketing tube radius: 41 µm
Capillary radius: 12 µm
Capillary thickness: 225 nm

*Calculating cross section*

As mentioned previously, an important aspect to the high power delivery capability of the ARHCF is the amount of overlap of the light with the glass of the fiber structure. Comsol enables the calculation of the effective mode area, through integrating the calculated electric field squared. You can then separate out over which domains that integration occurs. Because the glass and the air of the fiber are defined as different domains, this allows you to calculate the fractional effective area in the glass, compared to the total mode power.

Using this method with the final ARHCF design discussed here, the total amount of light in the glass elements of the ARHCF is only 0.006%. This is similar to values obtained by other groups working on these fibers. This extremely low light/glass overlap enables very high optical power delivery with high damage thresholds and high nonlinear coefficients.

*Design Degrees of Freedom*

In addition to developing the ideal design for the wavelength, power level, and bend radius of your given application, it is also important to know what is reasonable to expect from a fiber fabrication draw. You need to make sure that the design is both manufacturable, and understand what effect any small deviations from the design will have on the performance of your fiber. For instance, if small changes in the glass thickness or capillary diameters will have large impacts on the fiber's loss.

For each design parameter, a scan was done around the ideal design value to understand over what range of variance it would still produce a reasonable result.

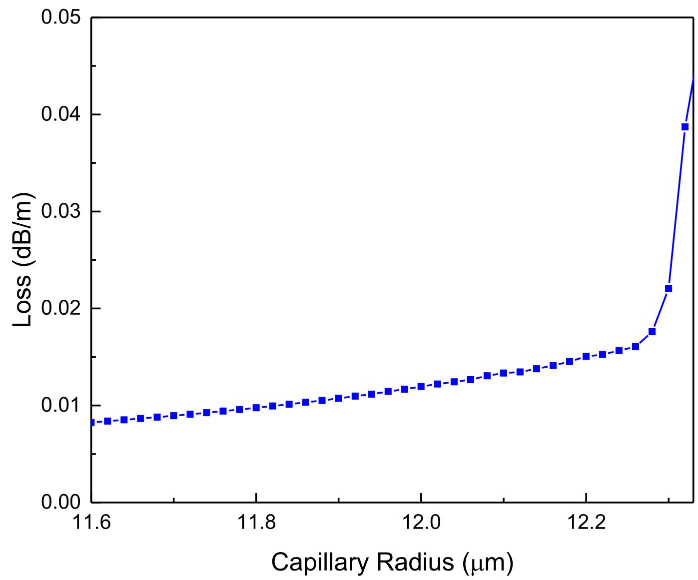



Fig. 14. Loss vs. capillary radius degree of freedom study.

First is shown a scan of the capillary radius, with all other variables set to their final design value. As can be seen in Fig. 14, from 11.6 to 12.2 µm, very little change in loss is observed. The peak that begins around 12.3 µm is caused by the capillaries beginning to touch one another. This plot shows that the design parameter of capillary size is not particularly critical, other than making sure that they do not fuse together.

Next, the inner radius of the jacketing tube was scanned, again keeping the rest of the variables fixed at their final design values. Figure 15 shows a similar curve to Fig. 14. When the inner radius was reduced to below 40.5 µm, the core was small enough that the capillaries began to

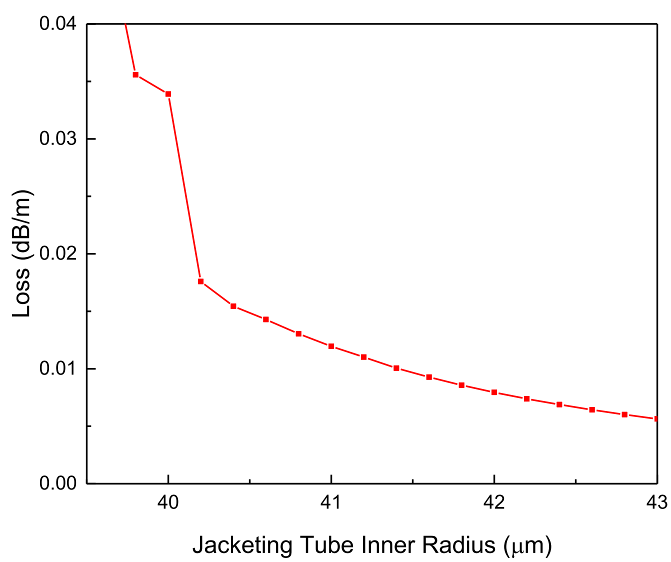



Fig. 15. Loss vs. jacketing tube inner diameter degree of freedom study.

touch. Apart from this sharp edge, the change in propagation is rather gradual, showing that this design parameter is similarly only critical on one side.

Next, a scan was done on the thickness of the capillaries. This parameter has not been as closely defined as the others yet, as it is more determined by the drawing process. Figure 16 shows the loss vs. thickness from 190 to 260 nm. The propagation loss decreases with increasing thickness, but over this relatively wide range of thicknesses, the loss only changes by 6 dB/km. Any loss within this range should be acceptable.

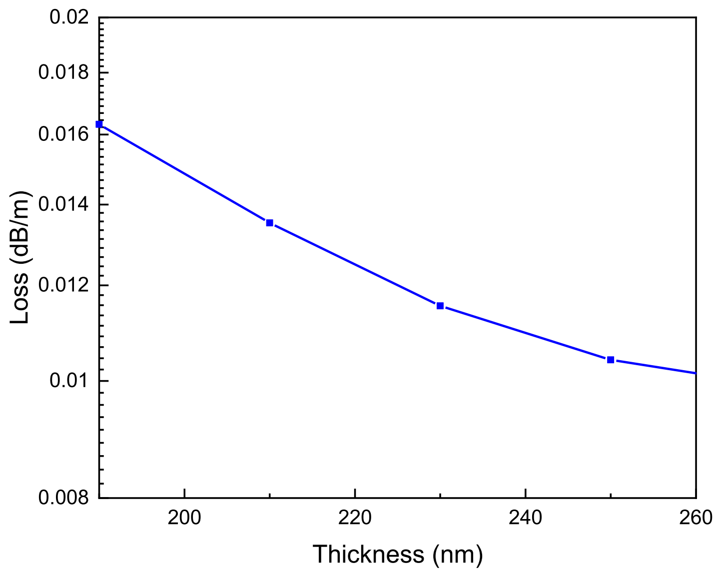



Fig. 16. Loss vs. thickness degree of freedom study.

A final scan was done looking at the transmission spectrum of the final fiber design. This ARHCF was designed for delivery of 1 µm laser light, but the exact wavelength of 1 µm laser systems can vary, so knowing the loss spectrum of the fiber will be important.

The final design parameters were used with a thickness values set to 225 nm. The spectral loss scan is shown in Fig. 17. This scan shows that over 1000 to 1120 nm, the loss is under 15 dB/km.

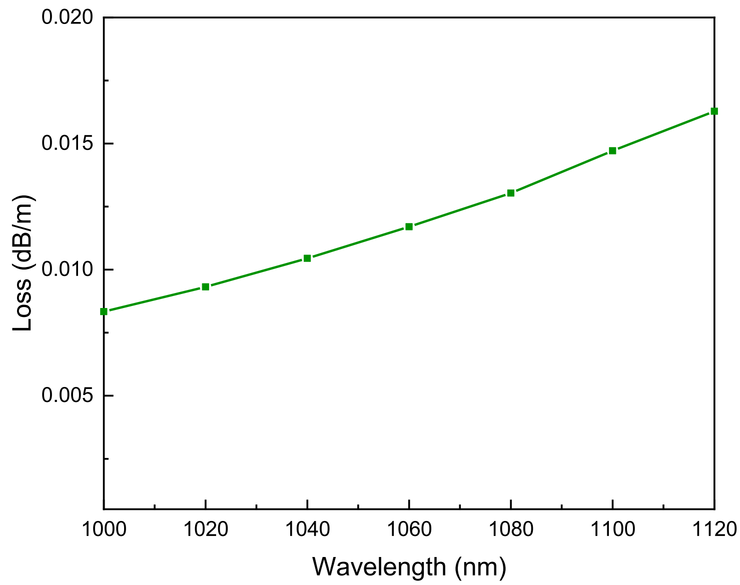



Fig. 17. Loss spectrum in the 1000-1120 nm regime.

## Task 2 – High power delivery fiber fabrication and characterization

The geometrical parameters of the fiber design were then delivered to the University of Central Florida (UCF) for fabrication. UCF has a 2 story fiber draw tower for fused silica optical fibers, and specializes in fabricating microstructured optical fiber using the stack and draw method.

*Fabricated fibers*

UCF delivered two ARHCFs to the PSU ARL EOC. The first was a pre-drawn fiber with specifications that closely matched the design – draw 690. The second fiber was drawn specifically for this program with attempts made to match the design specifications as closely as possible – draw 1155. Both fibers are shown in Fig. 18.

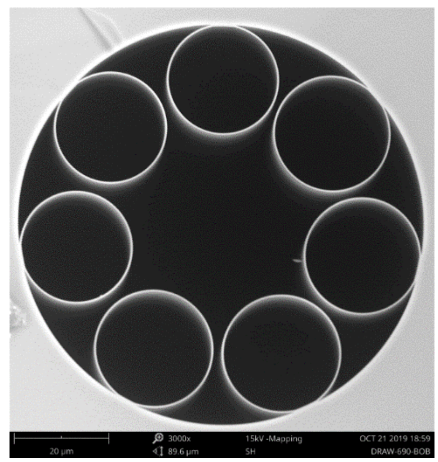
**Draw 690:**

Outer jacketing tube diameter: 171 µm

Inner jacketing tube diameter: 85 µm

Capillary diameter: 24 µm

Capillary thickness: 400 nm




**Draw 1155:**

Outer jacketing tube diameter: 167 µm

Inner jacketing tube diameter: 84 µm

Capillary diameter: 24 µm

Capillary thickness: 350 nm

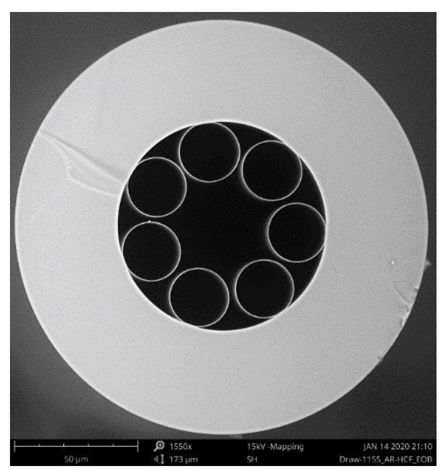



Fig. 18. SEM images of draws 690 and 1155.

The two fabricated fibers are compared to the design parameters in Table 1 below. The variation in the outer diameter will not affect the optical properties of the fiber. The capillary diameter is accurate for both drawn fibers, but the inner tube diameter has some slight variation. This change may impact the mode purity of the ARHCF. There is also significant variation in the capillary wall thickness. The disparity here could affect the propagation loss of the fibers.

Table 1. Comparison of design and drawn fibers.

| | **Draw 690** | **Draw 1155** | **Design** |
|---|---|---|---|
| **Outer Diameter (µm)** | 171 | 167 | 140 |
| **Inner Diameter (µm)** | 85 | 84 | 82 |
| **Capillary Diameter (µm)** | 24 | 24 | 24 |
| **Thickness (nm)** | 400 | 350 | 225 |

*Simulation comparison*

In order to understand how the differences in the drawn fibers' geometries will affect their optical properties, they were simulated in Comsol and compared to the original design. Table 2 shows the calculated losses of the fundamental mode, the first higher order mode, and the higher order mode extinction ratio (HOM ER) of the three designs.

Table 2. Loss comparison of design and drawn fibers.

| | **Draw 690** | **Draw 1155** | **Design** |
|---|---|---|---|
| **$LP_{01}$ Loss (dB/km)** | 19.6 | 12.0 | 11.9 |
| **$LP_{11}$ Loss (dB/m)** | 50.7 | 51.0 | 70.7 |
| **HOM ER** | 2587 | 4250 | 5941 |

The fundamental mode loss of draw 690 is increased compared to the design, due to the increased thickness of the capillaries which moves the first resonance closer to 1064 nm. The first higher order mode loss is slightly decreased, due to the increased inner tube diameter; however, the HOM ER remains sufficiently high.

The loss vs. wavelength is plotted in Fig. 19. This shows the beginning of the loss peak at resonance for Draw 690, which causes the fundamental mode loss to be higher at 1064 nm than the other two designs.

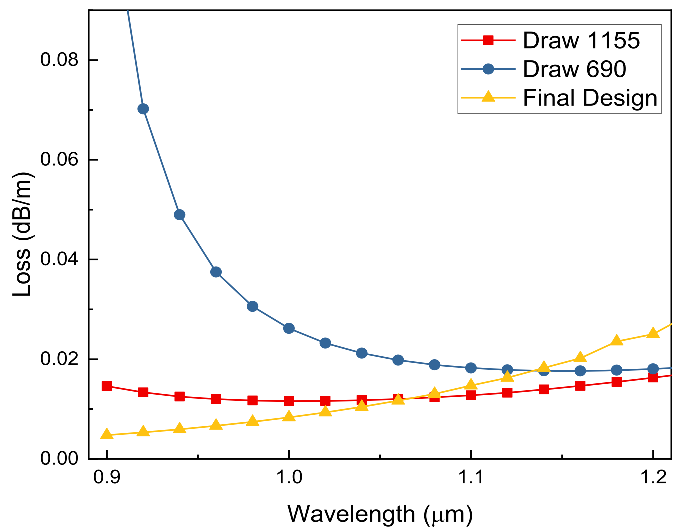



Fig. 19. Loss vs. wavelength comparison of the design and drawn fibers.

The response of the three fiber designs to bending was calculated, and is shown in Fig. 20. They all have similarly shaped curves, with both Draw 690 and Draw 1155 starting the slope of the first loss peak at slightly larger bend radii than the optimized design.

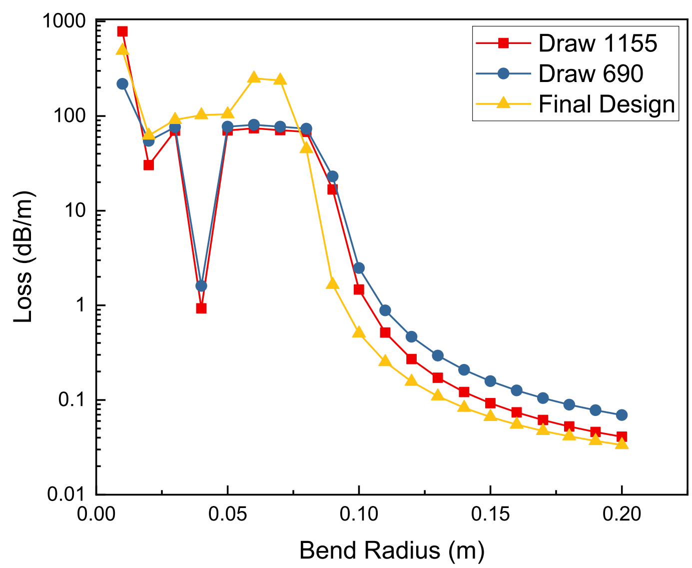



Fig. 20. Loss with bending for the drawn and designed fibers.

## Experimental Testing

*Low power characterization*

After modelling the fabricated designs in Comsol, they were characterized at low power. First, the transmission spectrum was measured used a supercontinuum source (NKT SuperK Compact), and an Optical Spectrum Analyzer (OSA). Fig. 21 shows the calculated loss from Comsol on top of the measured transmission spectrum of Draw 690.

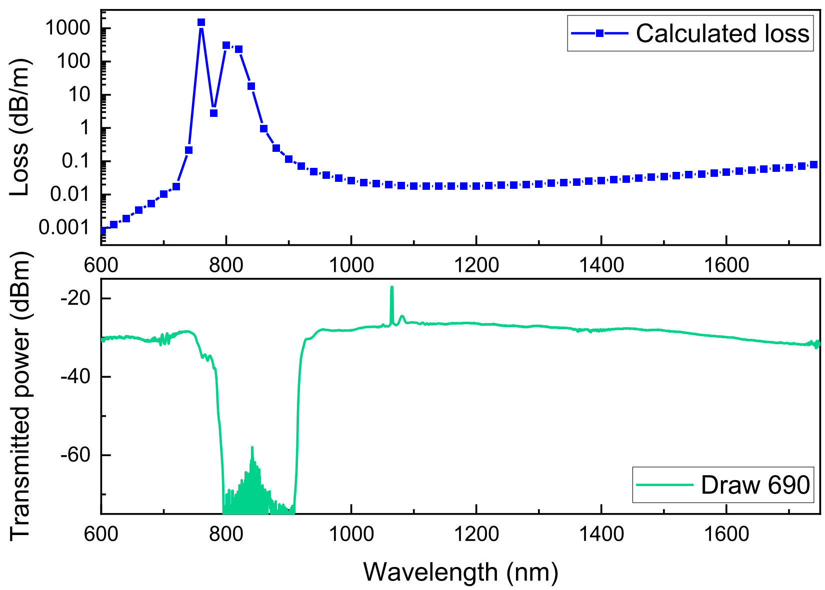



Fig. 21. Calculated and measured loss spectra of draw 690.

There is very good agreement between the simulated loss and the measured transmission. Both show a long, flat transmission window from 1000-1750 nm, with strong resonances at lower wavelengths. The width of the resonances is about 100 nm for both; however the center wavelength appears to be shifted by about 50 nm, with the measured resonance centered at 850 nm.

The location of these resonance is dependent on the thickness of the fiber capillaries. The equation to find the center of the resonance is as follows [2]:

$$\lambda_m = \frac{2t}{m}\sqrt{n^2 - 1} \qquad (m = 1,2,3 \ldots)$$

Here, $\lambda_m$ is the resonance wavelength, $t$ is the thickness of the silica, $m$ is the order of the resonance, and $n$ is the index of refraction of the silica. A shift in the estimated location of a resonance compared to its actual location implies an incorrect measurement of the capillary thickness. The value of the capillary thickness that was used in the Comsol model was obtained from the SEM image taken at UCF, shown in Fig. 22.

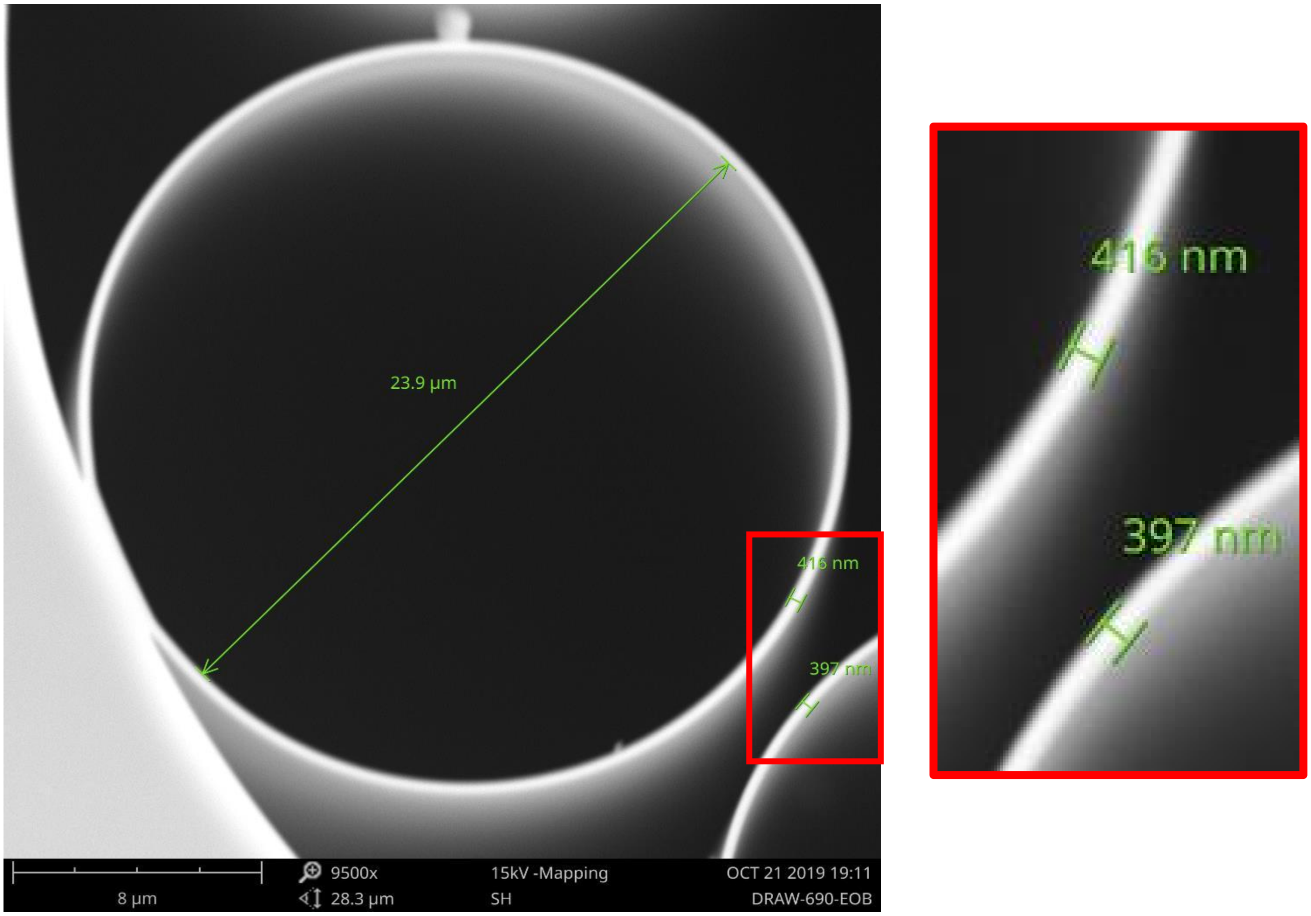



Fig. 22. SEM image of draw 690.

Looking at the zoomed in portion of the SEM image, the capillaries are not clearly in focus, and there is a variation between the two thickness measurements of ~20 nm. A change in thickness of 20 nm, corresponds to a wavelength shift of 40 nm in the resonance. Clearly the resolution of the SEM is at least ± 15 nm, leading to a resonance resolution of ± 30 nm.

This same comparison was done for draw 1155 and is shown in Fig. 23. Clearly, the calculated loss curve mirrors the measured transmission spectrum very closely, apart from the shift in the resonance location. This is again assumed to be caused by an inaccurate measurement of the capillary thickness from the SEM image. Also in Fig. 23 is an example mode image of draw 1155, showing a nearly Gaussian shape, with a heptagonal edge caused by the seven capillaries.

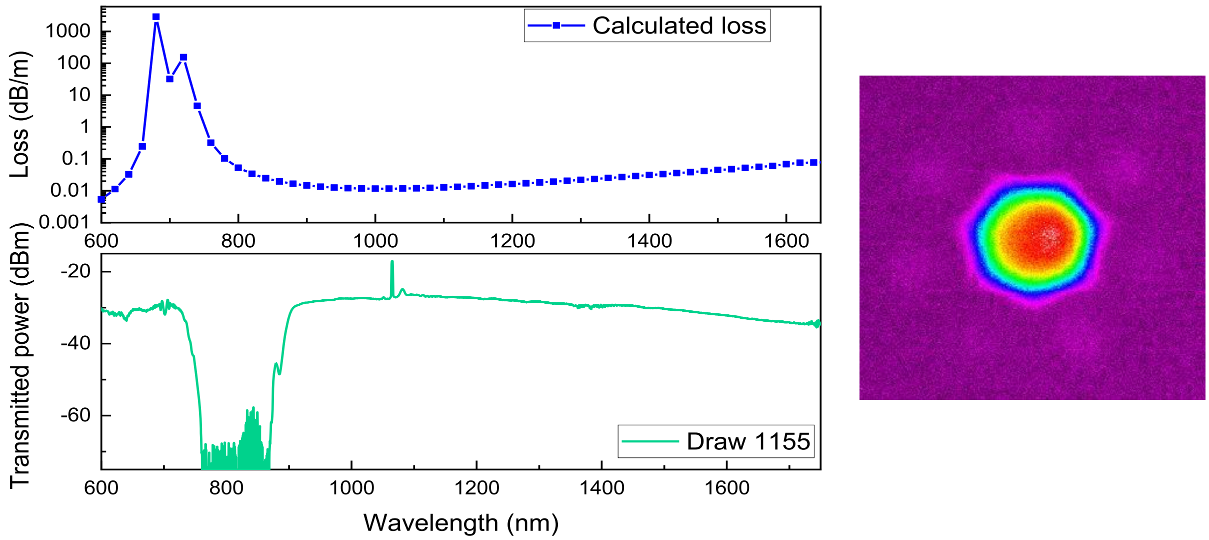



Fig. 23. Calculated and measured loss spectra of draw 1155, and mode image of draw 1155.

A bending loss test was then performed on draw 690. In this test, the transmission through a 3 m piece of ARHCF was measured as the fiber was coiled to different bend radii. In order to compare the loss vs. bend radius to that simulated in Comsol, the largest bend radius, 34 cm, was used as the reference for “straight”. Figure 24 below shows the comparison between the simulated loss and the measured loss with bending. The data both show similar curves of increasing loss with decreasing bend radius, as expected. There is a slight vertical offset between the measured data and the simulated data, but this is assumed to come from the inaccuracy of using 34 cm as the reference for straight propagation loss in the experiment.

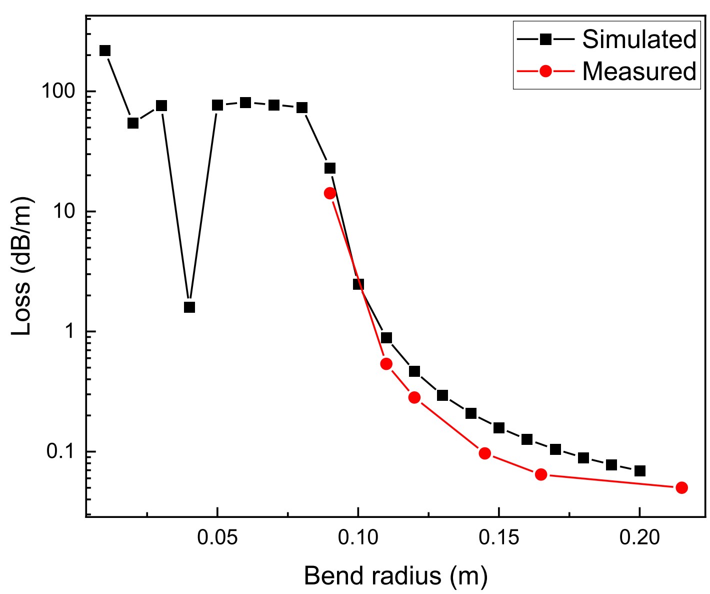



Fig. 24. Bending loss comparison of simulated and measured draw 690.

# Task 3 – High power testing

*High power testing*

After completion of the low power characterization, a high power testing setup was developed. The goal of the high power testing is to determine the power handling capability of the ARHCF for delivery of 1064 nm light. The source used is a 1 kW 1064 nm single mode laser from IPG (YLR-1000-SM). As the lowest stable power of this laser is approximately 100 W, significant attenuation needs to be built into the setup to allow for low power fiber alignment.

The laser output fiber head feeds into a water-cooled collimator, which collimates the beam to approximately 1 cm in diameter. The attenuation is achieved through two polarizing beam splitters and a half waveplate, shown in Fig. 25. The first polarizing beam splitter splits off 50% of the laser power, limiting our total available power to around 500 W. The half waveplate has an aperture of 1 cm, so in order to not damage the mount of the waveplate, a 1 cm aperture needs to be placed before it. The aperture cuts off about 13% of the laser power, corresponding to everything outside of the $1/e^2$ diameter. The waveplate can be rotated to minimize the power through the second beam splitter, cutting down the laser power to mW, enabling fiber alignment. The waveplate is then rotated to the maximum alignment position for high power testing, without changing the beam alignment.

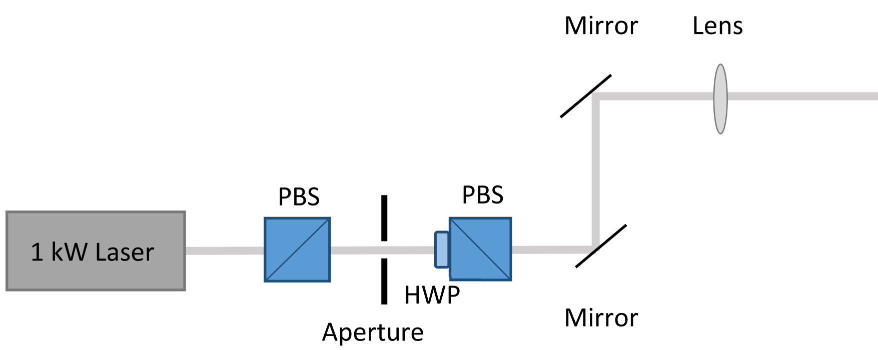



Fig. 25. Schematic of high power beam launch setup.

After the polarizing beam splitters, the beam is directed onto two 45° mirrors for position and angular alignment. The final optic is a focusing lens, chosen to closely match both the mode field diameter and the numerical aperture of the ARHCF. The mode field diameter of draw 690 is calculated to be 27.4 µm from Comsol, and draw 1155 is 26.7 µm and the numerical aperture (NA) was measured to be 0.039. The chosen lens has a focal length of 17.5 cm, which gives a spot size of 24 µm and an NA of 0.028. With this lens, coupling efficiencies slightly under 90% have been achieved. The full experimental setup is shown in Fig. 26 below.

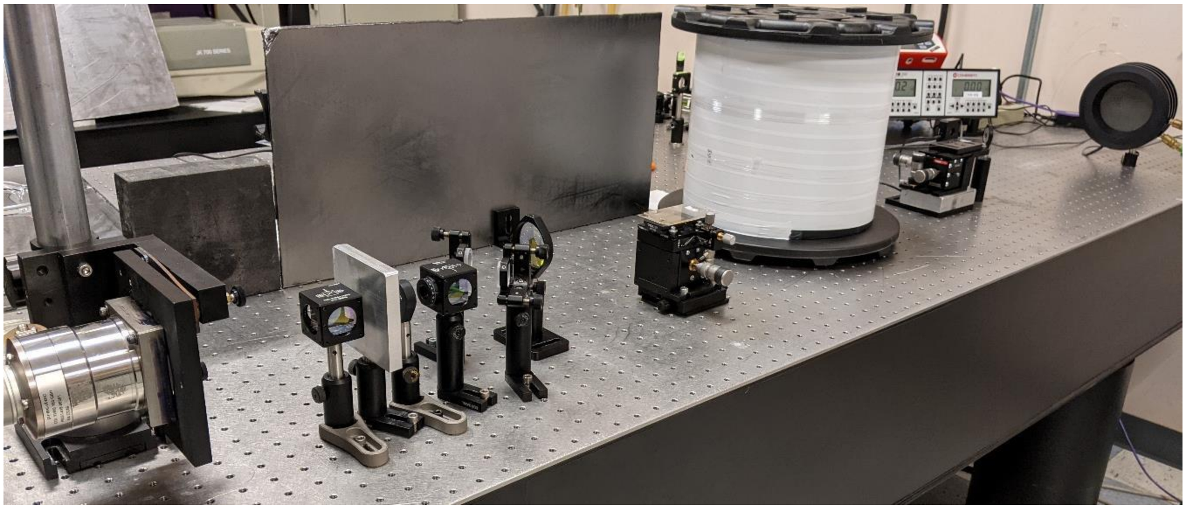


Fig. 26. Experimental setup for the high power testing.

The fiber is mounted on a Thorlabs Nanomax stage with a tip/tilt plate, which gives 5 degrees of freedom on the fiber position. The method of fixing the input end of the fiber to the translation stage is crucial. Any additional stress induced here by clamps or tape/epoxy will lead to increased light scattering and burning. Many attempts have been made at attaching the fiber end to v-grooves on top of the stage, but burning consistently occurs at relatively low powers. This burning is most likely caused by cladding light leaking into whatever material surrounds the fiber. An example of the burning of the epoxy holding the fiber in a quatz glass v-groove is shown in Fig. 27.

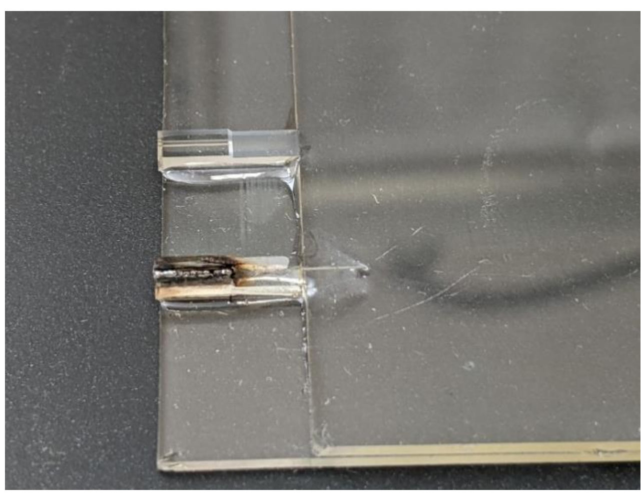


Fig. 27. Two quarts glass fiber v-grooves, one with burned epoxy after laser testing.

In order to get passed this limitation, the excess cladding light needs to be removed from the fiber and dissipated before reaching a flammable material. Palma-Vega et al. [4] was able to couple over 1 kW into a hollow core fiber by successfully removing this cladding light, so multiple methods from this reference were employed to increase our power handling.

The fiber was still placed in the quartz v-groove on the glass slide, but it was held in place by a high temperature epoxy, rated up to 350 °C. The beginning of the fiber was uncoated over the first 8 cm, and a high index refractive index liquid was applied over the uncoated section of fiber on the glass slide. This liquid will draw out cladding light before it reaches the coated section of the fiber.

Using these methods, significantly higher powers were able to be coupled into the ARHCF, however the coupling efficiency at high laser power is reduced compared to low alignment powers. At low power, ~90% can be coupled into the ARHCF, whereas when the power is increased into the tens of Watts, the efficiency drops to ~70%. There is still heating that occurs at the v-groove, as evidenced on a thermal camera, and at high laser powers the v-groove temperature can quickly climb to over 100 °C. It is believed that this heating causes some misalignment of the fiber which leads to the reduced coupling efficiency.

Even with the reduced efficiency, the current setup enabled the coupling of up to 170 W of CW laser power, as shown in Table 3 and Fig. 28.

Table 3. High power laser transmission and efficiency testing results.

| Input (W) | Output (W) | Efficiency (%) |
|---|---|---|
| 33.8 | 24.7 | 73 |
| 54.4 | 42.6 | 78 |
| 79.2 | 61.1 | 77 |
| 103.9 | 70.2 | 68 |
| 120.4 | 86.3 | 72 |
| 153.4 | 110.24 | 72 |
| 169.9 | 116.0 | 68 |

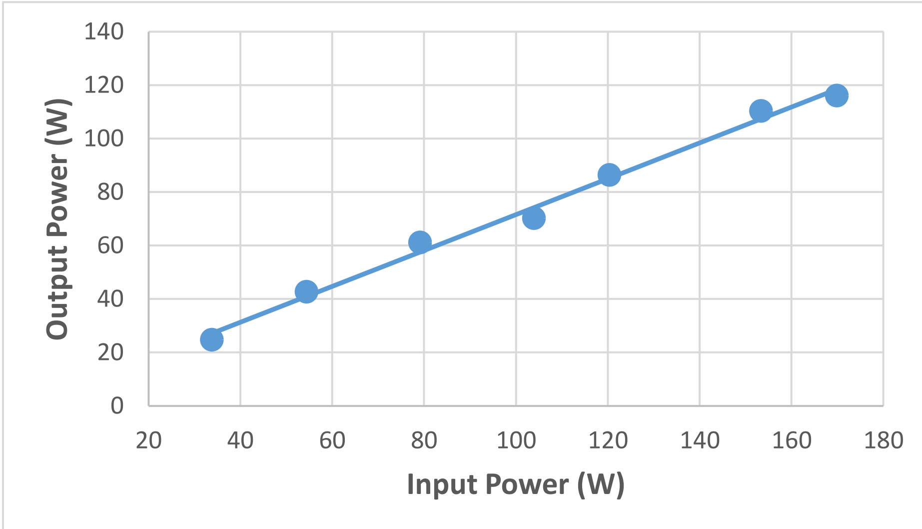



Fig. 28. High power laser testing results.

The heating of the v-groove at increasing laser powers meant that the input facet of the fiber had to be continually realigned at each power level in order to achieve 70% coupling efficiency. At 170 W input, the v-groove again burned, as shown in Fig. 27.

To date, testing has shown that the ARHCF can withstand CW laser powers of at least 170 W, or 0.7 $GW/cm^2$. In order to push past this current power limit, the facet heating and coupling efficiency need to be addressed.

## Task 4 - Mid-Infrared Fiber Design and Testing

A design for an ARHCF that guides in the mid-infrared regime has been optimized in Comsol. As the wavelength of guidance gets larger, the fiber size will also scale up. The same principles outlined in Task 1 still apply. The thickness of the capillaries will determine the locations of the resonances, and the ratio of the core size to the capillary size will determine the modes that are guided. The goal of this fiber design is to have single mode guidance throughout the 3-5 µm window.

An important consideration in this window is the absorption of silica. The loss increases exponentially with wavelength, which will affect the propagation loss of the ARHCF. In order to accurately take this into account, the absorption of fused silica as a function of wavelength was plotted and fit to a curve. This function was then input into Comsol.

Scans of various core and capillary sizes were done in order to find the design that gives the lowest loss across the entire 3-5 µm window. The final design is shown below.

*Final Design:*

Tube outer diameter: 400 µm

Tube inner diameter: 236 µm

Capillary diameter: 68 µm

Capillary thickness: 1 µm

The loss vs. bending and loss vs. wavelength of the final design are shown in Figs. 29 and 30 below.

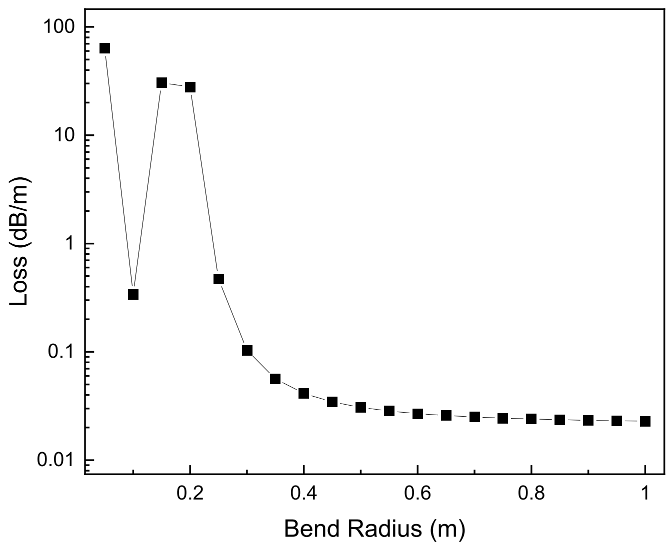



Fig. 29. Loss vs. bend radius for final mid-infrared fiber design.

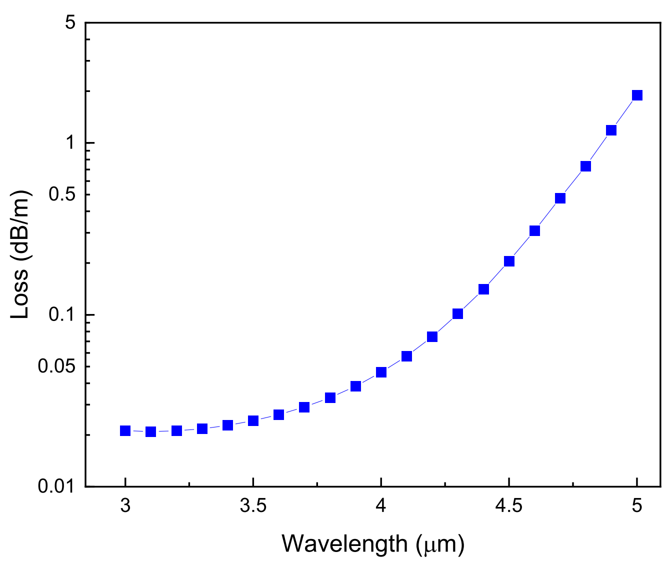



Fig. 30. Loss vs. wavelength for final mid-infrared fiber design.

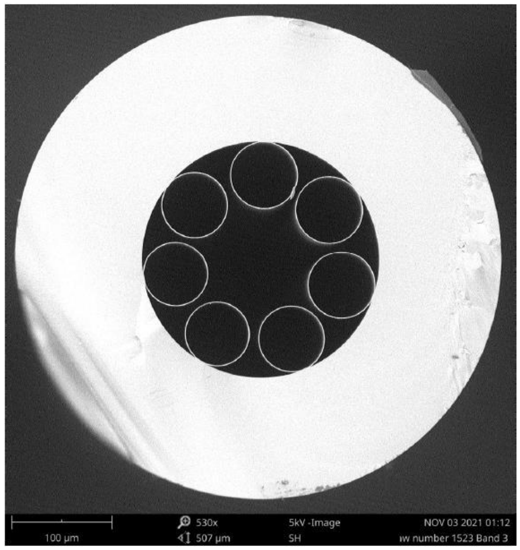



Fig. 31. SEM image of drawn mid-infrared ARHCF.

The fiber dimensions were sent to UCF on 12-2-2020. Due to the pandemic and a failed furnace on their draw tower, the fiber was not delivered until 11-10-2021. This long delay caused work on this program to stop for several months while waiting for the fiber delivery and led to a required 3 month No Cost Extension.

The drawn fiber cross section is shown in Fig. 31. The dimensions of the drawn fiber closely match those of the design.

Drawn fiber:

- Tube outer diameter: 475 µm
- Tube inner diameter: 235 µm
- Capillary diameter: 65 µm
- Capillary thickness: 0.93 µm
- Core diameter: ~100 µm

The fiber was tested with a Leukos Electro MIR 4.8 superconitnuum source and Thorlabs 205C OSA that were purchased on a 2020 AFOSR DURIP grant (FA9550-20-1-0141). The measured transmitted spectrum through 4.4 and 25.7 m of the ARHCF on a 35 cm diameter spool is shown in Fig. 32. The absorption lines at 3.5 µm and 4.3 µm correspond to HCl and $CO_2$, respectively [5]. This transmitted signal shows intensity up to about 4.6 µm. Recent work shows similar ARHCF made from fused silica with high losses above 4 µm [5], such as Pierściński et al. with 8.5 dB/m at 4.57 µm [6] and Nikodem et al. with 6 dB/m at 4.54 µm [7]. Given that we clearly have signal at 4.6 µm through 35 m of fiber, these initial results are very promising for the performance of this fiber in the 3-5 µm window.

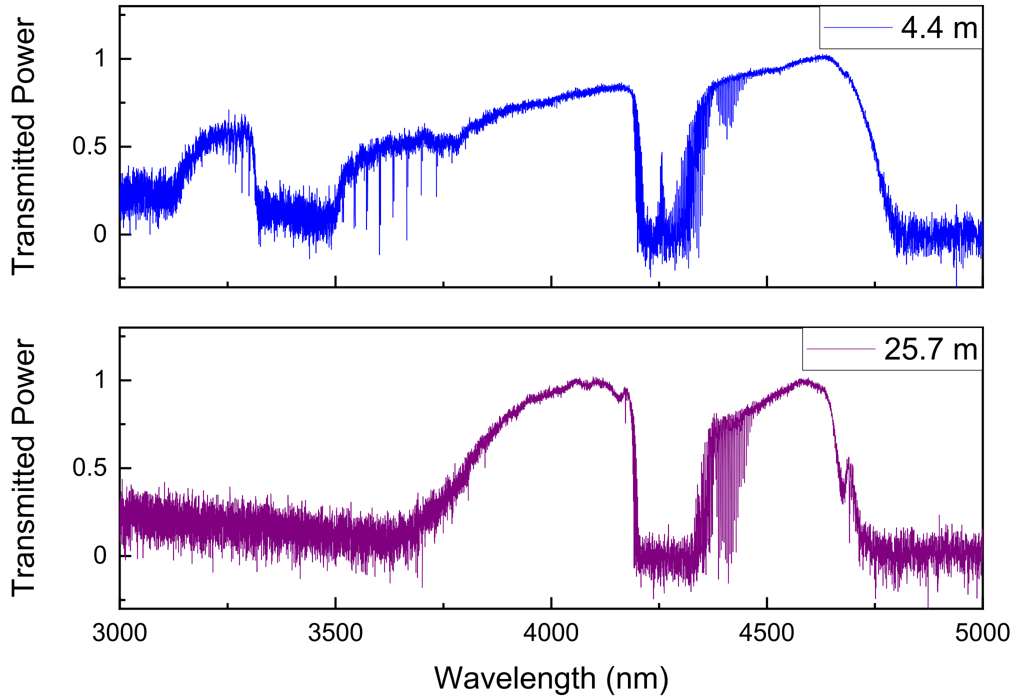



Fig. 32. Transmitted signal of a Leukos Electro MIR supercontinuum source through MWIR ARHCF.

Comparing the measured transmission spectrum to the simulated loss, there is good agreement on the loss edges at ~3.2 and ~4.7 μm. Fig. 33 shows this comparison, and apart from the absorption lines, the transmitted power and the simulated loss mirror each other closely.

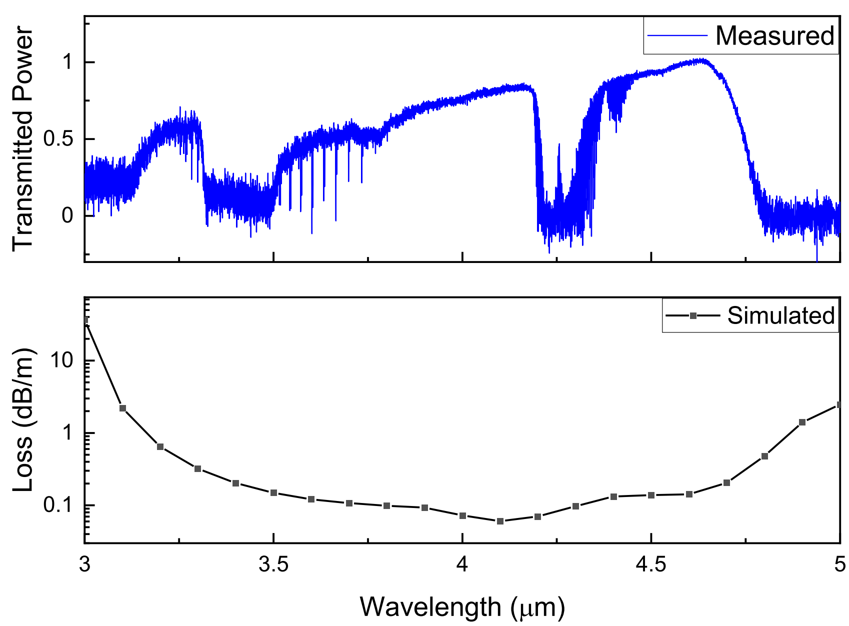



Fig. 33. Comparison of measured transmission through 4.4 m of ARHCF to simulated loss spectrum.

The loss edge at ~4.7 µm is expected and is caused by the absorption of the fused silica. Even though the overlap of the core light with the glass of the fiber is very low, the extremely high absorption levels of silica in the mid-infrared start to dominate the loss at this wavelength.

The loss edge at the lower wavelength edge was not expected, and the model had to be revisited in order to investigate the cause of this loss. A larger scan of the propagation loss vs. wavelength was done at the bend diameter of the test setup (35 cm). A large peak of very high loss was found from 2.4-3 µm, shown in Fig. 34. When looking at the mode of the fiber in this wavelength range, the core mode has coupled into the mode of a capillary. This mode coupling caused by bending was discussed in the fiber design section (Task 1) and is a known occurrence with ARHCF.

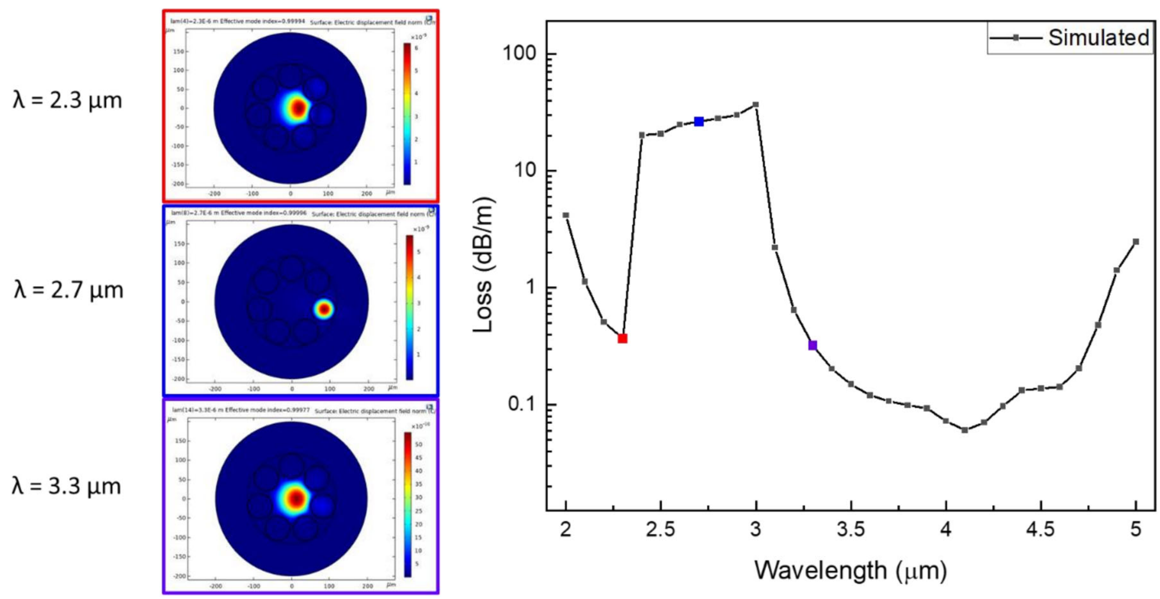



Fig. 34. Simulated loss spectrum and mode images at a 35 cm bend diameter.

This fiber was designed for a transmission bandwidth of 3-5 μm. If a lower loss at the lower wavelength end is desired, the coupling into the capillary mode can be eliminated by simply using a larger bend diameter. Shown in Fig. 35 is the calculated loss vs. wavelength as the fiber is bent in the +y direction for various bend diameters. At a bend diameter of 90 cm, the bend resonance is eliminated from the transmission window, and the loss at 3 μm drops below 0.01 dB/m.

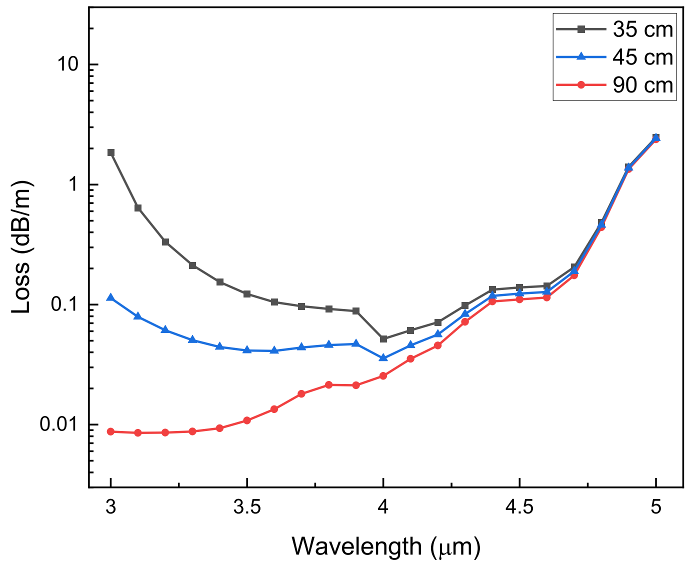



Fig. 35. Simulated loss spectrum at various bend diameters.

After getting an understanding of the transmission spectrum, the loss at two wavelengths was measured using quantum cascade lasers. Cut back measurements were done at 4.05 and 4.63 μm. The results of the measurements are shown in Fig. 36 below.

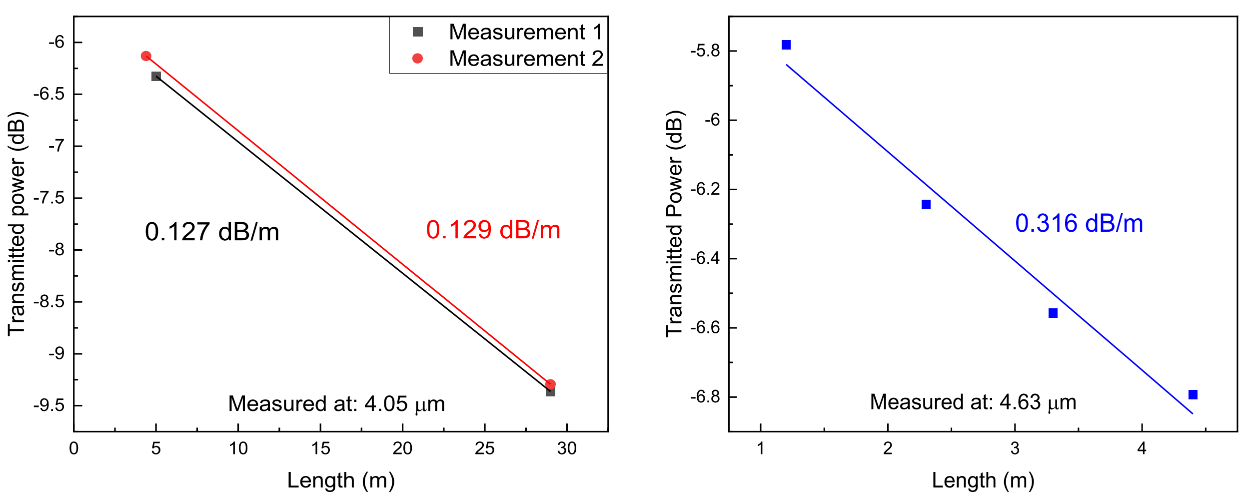



Fig. 36. Cutback measurements at 4.05 μm and 4.63 μm.

This measured loss was compared to the simulated loss and is shown in Fig. 37 below. The two measured values fit well into the calculated spectrum. At 4.05 µm, the measured loss is 0.128 dB/m and the calculated loss is 0.07 dB/m. At 4.63 µm, the measured loss is 0.316 dB/m and the calculated loss is 0.165 dB/m. The slightly higher measured loss values are to be expected due to non-uniformities in the as-drawn fiber compared to the perfect simulated version.

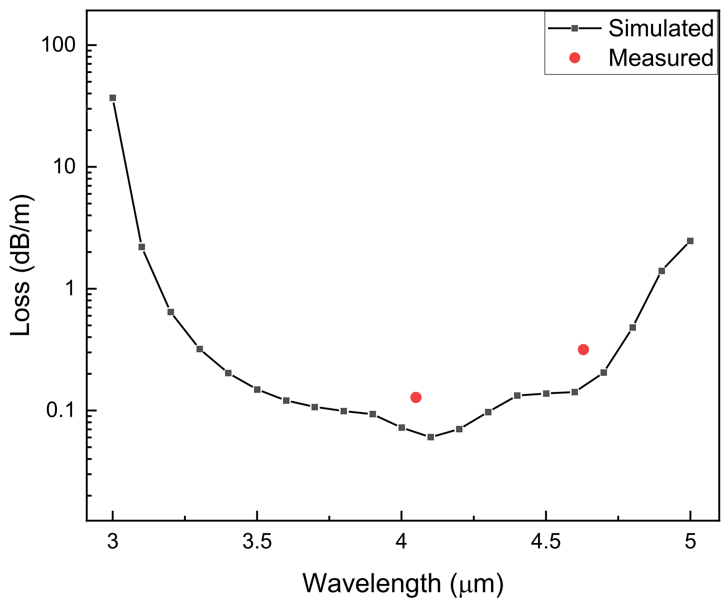



Fig. 37. Comparison of measured loss values to simulated loss spectrum.

The measured loss of 0.316 dB/m at 4.63 µm is significantly lower than previously published values in this wavelength range for silica-based hollow core fibers (8.5 dB/m at 4.57 µm [6] and 6 dB/m at 4.54 µm [7]). When compared to IR glass fibers, this value is similar to that of commercially available single mode InF fibers, ~0.25 dB/m at 4.5 µm [8], and only slightly higher than state of the art Chalcogenide fibers at 0.1-0.2 dB/m [9]. Silica fiber manufacturing is mature and the drawn fiber is significantly more robust than InF or Chalcogenide, with recent reports showing the capability to draw up to 1.7 km of ARHCF with very low loss [10].

The reason for such low propagation loss at a wavelength where the silica absorption is ~1500 dB/m is the strong core confinement, which was calculated to only allow for 0.005 % percent of the fundamental mode's power overlapping with the glass. Such strong confinement enables pushing the transmission of a fused silica-based fiber well beyond its traditional limits, and makes silica ARHCF a viable option for MWIR transmission past 4 µm.

The above cutback measurements were done with the fiber bent to a diameter of 35 cm. As shown in Fig. 35, at 4.05 µm a bend dependent loss is predicted by simulation. This was tested experimentally through bending ~5 m of the ARHCF to various bend diameters, and measuring the transmitted power. As expected, as the bend diameter decreased, the transmitted power decreased slightly, shown in Fig. 38a). The calculated loss from the cutback measurement done at 35 cm was used to calculate the loss at each of the measured bend diameters, as is shown in Fig. 38b). At large diameters, the loss drops under 0.1 dB/m.

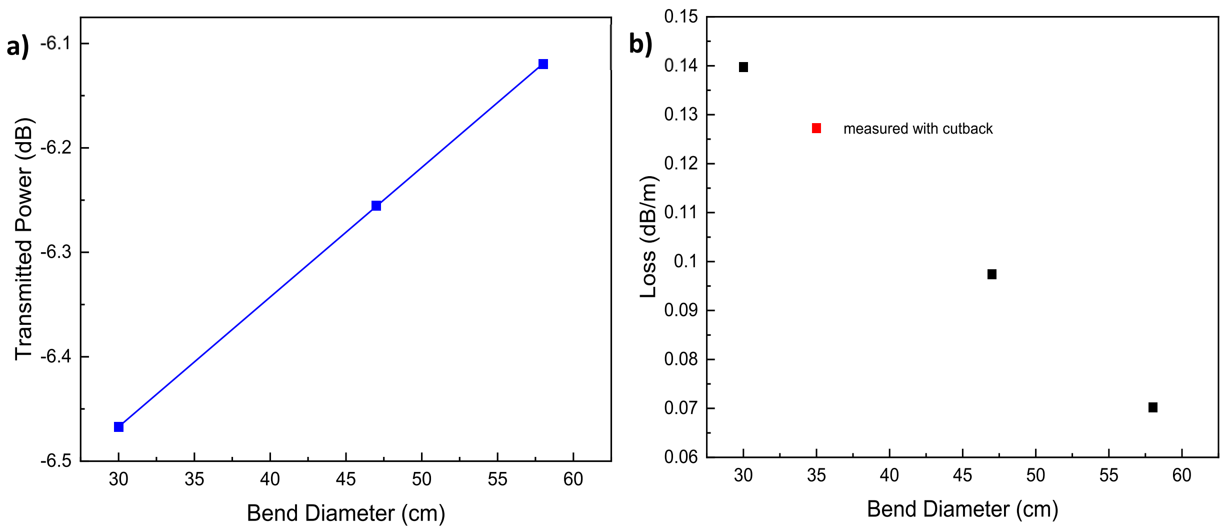



Fig. 38. a) Transmitted power vs. bend diameter at 4.05 μm. b) Estimated loss vs. bend diameter at 4.05 μm.

## Conclusion

A thorough investigation into the design of anti-resonant hollow core fiber has been performed. Using Comsol Multiphysics, each design parameter was studied for how it affected the guidance and loss of the modes of the fiber. This understanding was used to optimize two designs of fiber, one for low loss around 1 μm for high power laser delivery, and the other for broadband transmission in the mid-infrared.

The two fiber designs were drawn at the University of Central Florida, and delivered to the Penn State ARL EOC. A high power testing setup was developed, based on a single mode, 1 kW 1060 nm CW laser. The ARHCF was tested, and powers up to 170 W were able to be coupled into the fiber. Heating at the fiber facet limited the total power able to be coupled into the fiber. Recent research has shown that coupled power levels can be significantly improved through the use of an end cap on the input facet of the ARHCF [11]. Through an AFOSR DURIP grant (FA9550-22-1-0122), a $CO_2$ laser splicer and glass processing system has been acquired, which has the ability to splice end caps to hollow core fiber. Future efforts in high power delivery testing will incorporate end caps in order to mitigate facet heating and improve coupling efficiencies.

The mid-infrared fiber was tested with a broadband source and Optical Spectrum Analyzer, as well as two quantum cascade lasers. Propagation loss and bending loss were measured as a function of wavelength. We have shown a silica-based ARHCF with guidance up to 4.6 μm with relatively low loss, which is a significant improvement over previously published work. This shows that the wavelength region where alternative glasses need to be used can be pushed higher than previously considered. Silica-based ARHCF can be a viable option for MWIR transmission in the 3-5 μm region, an important atmospheric window for applications such as infrared counter measures and remote sensing.

## Publications

1. Amy Van Newkirk, Julian Martinez Mercado, Enrique Antonio Lopez, Rodrigo Amezcua Correa, and Axel Schülzgen, "High power laser delivery using anti-resonant hollow core fiber", Proc. SPIE 11826, Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications XV, 118260D (6 August 2021).

2. Amy Van Newkirk, Julian Martinez Mercado, Enrique Antonio Lopez, Rodrigo Amezcua Correa, and Axel Schülzgen, "Anti-Resonant Hollow Core Fiber for High Power Laser Delivery", IEEE Research and Applications of Photonics in Defense, (2021).

3. Amy Van Newkirk, Enrique Antonio Lopez, Rodrigo Amezcua Correa, and Axel Schülzgen, "Pushing the transmission of silica hollow core fiber towards 5 µm", Optica Advanced Photonics Congress, (To be presented July 2022).

## Invited Talks

1. Amy Van Newkirk, "Anti-Resonant Hollow Core Fiber for High Power Applications", Symposium on Optics Applications, Sustainability and Energy, Universidad Autónoma de Nuevo León (5 November 2021).

## Collaborations

1. University of Central Florida – UCF was a subcontractor who fabrication the anti-resonant hollow core fiber used throughout this work.

## Transitions

Discussions have been had with several researchers at AFRL about transitioning the MWIR work forward. These researchers include Gary Cook, Carl Liebig, and Kent Averett.

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2. F. Yu and J. C. Knight, "Negative Curvature Hollow-Core Optical Fiber," IEEE J. Select. Topics Quantum Electron. **22**, 146–155 (2016).

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4. G. Palma-Vega, F. Beier, F. Stutzki, S. Fabian, T. Schreiber, R. Eberhardt, and A. Tünnermann, "High Average Power Transmission Through Hollow-core Fibers," in *Laser Congress 2018 (ASSL)* (OSA, 2018), p. ATh1A.7.

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