DESIGN OF TOPAS BASED HOLLOW CORE ANTIRESONANT FIBER FOR TERAHERTZ WAVEGUIDE

by

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This thesis titled, "DESIGN OF TOPAS BASED HOLLOW CORE ANTIRESONANT FIBER FOR TERAHERTZ WAVEGUIDE," submitted by Pritom Datta, Roll No.:0416062280, Session: April 2016, has been accepted as satisfactory in partial fulfilment of the requirement for the degree of MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING on 10^{th} April 2023.

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This is hereby declared that the work titled " **Design of Topas based hollow core anti-resonant fiber and exploring low loss for terahertz waveguide** " is the outcome of research carried out by me under the supervision of Dr. Mohammad Faisal, in the *Department of Electrical and Electronic Engineering*, *Bangladesh University of Engineering and Technology (BUET)*, Dhaka 1000. It is also hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma and that all sources are acknowledged.

Signature of the Candidate

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Pritom Datta

Dedication

Dedicated to my beloved parents and wife.

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Abstract

Novel low loss fiber for THz application offers great potential for optical fiber study. A novel topas based antiresonant hollow core fiber is designed and numerically characterized by finite element method (FEM) based mode solver software. Comsol Multiphysics were used to design and full-vector finite element method with perfectly matched layer (PML) boundary condition is used to investigate the wave guiding property including single mode operation, effective material loss, confinement loss, V-parameter and bending loss.

We have found confinement loss as low as 0.000127 dB/m (at 1 THz) and effective loss as low as 0.081236 dB/m (at 1 THz). Our antiresonant fiber offers lower propagation loss in the range of 0.9 THz – 1.4 THz for all models. We have found the lowest propagation loss of 0.083991 dB/m at 1 THz. From 0.77THz to 1.4 THz range of spectrum, flat dispersion was observed. For varying bending radius, very low decreasing bending loss with increasing bending radius was shown. V-parameter was below 2.405 which demonstrates single mode fiber transmission in this study.

This unique design of HC-ARF offers ultra flat dispersion profile over a wide THz spectrum. A latest cyclo-olefin polymer (COP) based material, trade name Topas, is chosen as the background material for proposed model because of its unique advantages over other materials. Moreover, it has lower specific gravity, chemical resistance at elevated temperature, higher transparency, lower melt flow index etc. Furthermore, the physical properties of Topas are also suitable for high quality fiber drawing. Fabrication feasibility and tube-based design allow more suitable low loss profile for THz communication.

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List of Abbreviation

Symbol	**Meaning**
THz	Terahertz
OFs	Optical Fibers
PCFs	Photonic Crystal Fibers
PMMA	Polymethyl Methacrylate
HDPE	High density polyethylene
COP	Cyclo-Olefin Polymer
MSM	Metal Semiconductor Metal
HC-ARF	Hollow Core Anti Resonant Fiber
PCA	Photoconductive Antenna
EML	Effective Material Loss
FEM	Finite Element modeling
PML	Perfectly Matched Layer
PEHD	Polyethylene High-Density
PTFE	Polytetrafluoroethylene
COC	Cyclic Olefin Copolymer

Chapter 1

Introduction

1.1 Terahertz spectrum

Terahertz waveguide [1] is one of the significant band (0.1Thz to 10Thz)within microwave and infrared ranges and offers great potential for researching in scientific community. Currently this specific range is actively being researched for various applications in optical fiber communication , astronomy, spectroscopy, security screening, medical imaging, short range high speed communications, pharmaceutical quality control, military security, biomedical engineering, and sensing applications [2-6] etc. Though an outstanding progress has been achieved in designing convincing fiber models for best suitable application, it is still an ongoing imploring challenge to find the reliable design for compact, efficient and low loss THz waveguide.

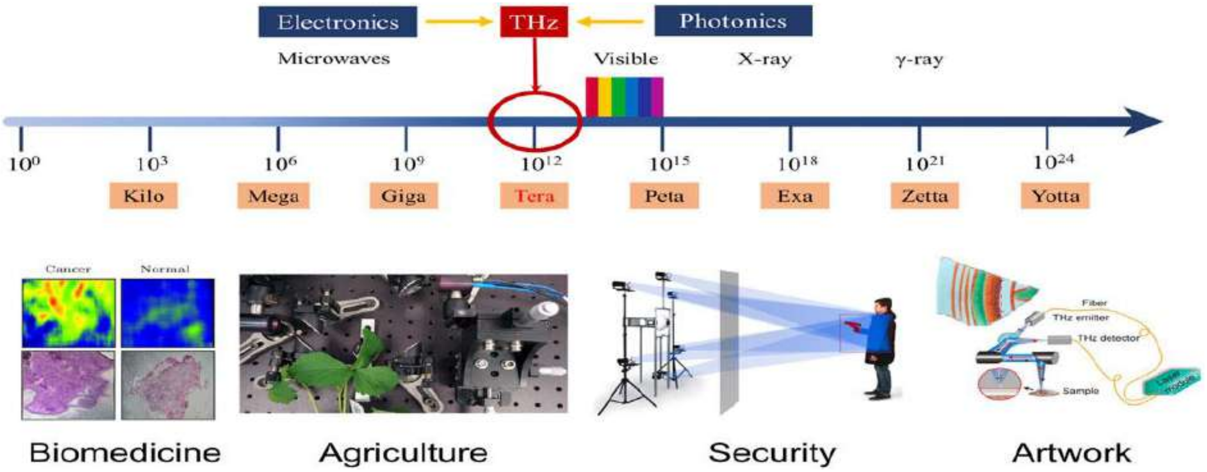


Figure 1. 1: Thz spectrum and its application adapted from ref. [19]

1.2 Terahertz Spectrum’s Application

The Terahertz (THz) spectrum, which lies between the microwave and infrared regions of the electromagnetic spectrum, has a variety of applications in several fields. Some of the major applications of the Terahertz spectrum are Imaging, Spectroscopy, Security, Communications, Astronomy, Materials characterization, Environmental monitoring etc [2-6].

Terahertz radiation can penetrate materials such as plastics, paper, and fabrics, making it ideal for non-invasive imaging applications. It can also be used for medical imaging, including detecting skin cancers and imaging teeth. Terahertz spectroscopy is used to analyze the chemical composition of materials [6]. The unique absorption and transmission properties of Terahertz radiation make it an excellent tool for identifying molecules and analyzing chemical reactions. Terahertz radiation can be used to detect hidden objects such as weapons, explosives, and drugs. It can also be used for body scanning at airports to detect concealed objects. Terahertz radiation can be used for high-speed wireless communication systems, providing much higher data rates than current technologies. Terahertz radiation is used in astronomy to study the early universe and to analyze the composition of planets, stars, and galaxies. Terahertz radiation is used to study the properties of materials such as semiconductors, polymers, and ceramics.Terahertz radiation can be used to monitor the environment, including air pollution, greenhouse gases, and atmospheric conditions.

Overall, the Terahertz spectrum has a wide range of applications in various fields, making it an increasingly important area of research and development.

1.3 Microstructured Fiber

The usual core diameter of micro structured fibers is a few microns to tens of microns, and the cladding diameter is a few tens to hundreds of microns [34]. The air holes that are placed in a periodic lattice pattern with a pitch of a few microns and typically have a diameter of a few hundred nanometers travel along the length of the fiber. The size and configuration of the air holes can be changed to regulate the optical characteristics of the fiber, including dispersion, birefringence, and nonlinearity.

The specific dimensions of a micro structured fiber can vary depending on the intended application, and different designs may be optimized for different properties. For example, fibers designed for sensing applications may have a larger cladding diameter to increase sensitivity to external stimuli, while fibers designed for high-power applications may have a smaller core diameter to increase light confinement and reduce nonlinear effects.

A micro structured fiber, also known as a photonic crystal fiber, is a type of optical fiber that has a periodic structure of air holes running along its length. These holes create a pattern of alternating high and low refractive index regions, which give the fiber unique optical properties. Micro structured fibers offer several advantages over conventional optical fibers.

The periodic structure of the fiber can confine light within a small core region, allowing for higher light intensities and more efficient light transmission. The unique structure of the fiber can support a wide range of wavelengths, making it useful for a variety of applications, such as optical sensing, nonlinear optics, and supercontinuum generation. The high level of symmetry in the fiber structure allows for precise control of the polarization of the transmitted light. The unique properties of micro structured fibers, such as dispersion properties, birefringence, and nonlinearity, can be tailored by adjusting the size and shape of the air holes, making them useful for a variety of applications.

Micro structured fibers have many practical applications, including telecommunications, sensing, and biomedical imaging. They are also used in fiber lasers and amplifiers, as well as in high-power fiber-optic delivery systems.

1.4 Solid Core Fiber

Solid core fiber is a type of optical fiber that has a continuous, solid glass core surrounded by a cladding layer with a lower refractive index. The core is typically made of silica or other types of glass, and the cladding layer is made of a different type of glass with a slightly lower refractive index.

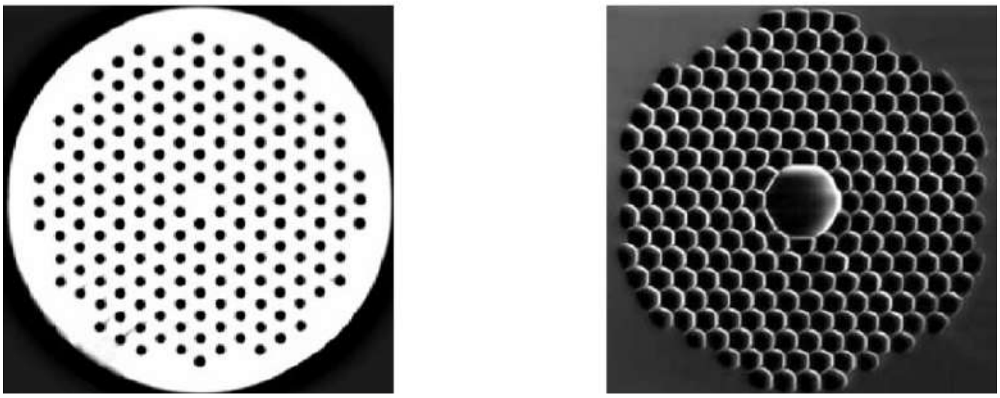


Figure 1. 2 : a) Solid Core Fiber b) Hollow core fiber adapted from ref. [36]

Solid core fibers are commonly used in telecommunications and other high-speed data transmission applications. They offer low signal attenuation and high bandwidth, allowing for the transmission of high-speed data over long distances. They are also highly reliable, with low signal loss due to fiber bending or other types of mechanical stress. Solid core fibers come in different sizes, typically ranging from a few microns to a few hundred microns in diameter. The core diameter is one of the key parameters that determines the fiber's performance, with smaller core diameters allowing for greater light confinement and higher transmission speeds. However, smaller core diameters also lead to greater signal attenuation, making it more difficult to transmit data over longer distances.

In addition to telecommunications, solid core fibers are also used in a variety of other applications, including fiber lasers, sensing, and biomedical imaging. Their high reliability and low signal loss make them well-suited for harsh environments and high-power applications.

1.5 Hollow Core Fiber

Hollow core fiber is a type of optical fiber that has a central core which is not solid, but instead is a hollow tube. This core is typically made of air or a low-density gas, and is surrounded by a cladding material that guides the light along the fiber.

The unique structure of hollow core fiber offers several advantages over traditional solid-core fibers. Because light travels through air more quickly than it does through glass, hollow core fibers can achieve lower latency and higher bandwidth than solid-core fibers. Additionally, they can transmit light across a broader range of wavelengths, making them useful in a variety of applications, including telecommunications, sensing, and laser delivery.

Hollow core fibers can be challenging to manufacture, but recent advances in

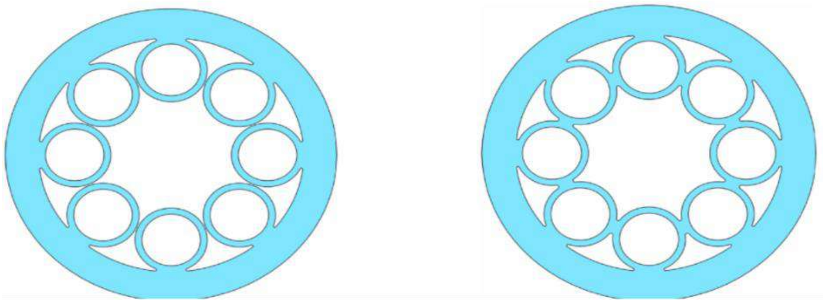


Figure 1. 3 : Hollow core anti-resonant tube lattice structure

technology have made them more accessible and practical. They are particularly useful in applications that require high-speed data transfer, low-latency communication, or high-power laser delivery.

Hollow-core fiber guides light essentially within a hollow region, so that only a minor portion of the optical power propagates in the solid fiber material (typically a glass). A particularly simple design (also leading to simplified production) is that of the revolver hollow-core fibers [21] containing a pattern of silica rings (with circular or elliptical cross-section) around the hollow core; those are not using a photonic bandgap and cannot be considered as photonic crystal fibers. The fiber preform can be made relatively simply by arranging a number of silica capillaries, and these result in thin glass membranes after drawing into a fiber. A more refined version contains additional smaller rings nested within the larger rings [22, 33], and can provide further reduced propagation loss. A loss reduction can also be achieved already by slightly separating the tubes, avoiding nodes where they would touch each other. The term negative curvature fibers underline the boundary curvature in a direction opposite that to a ring around the core. Other terms, containing the attribute antiresonant, emphasize the aspect of loss reduction by designing the glass structure for optical anti-resonance, i.e., suitable relative phase changes for reflection at different interfaces.

1.6 Objective of This Research

The objective of this thesis is to analysis hollow core anti resonant fiber and find low loss properties for negative curvature capillary tubes.. The aim is to contribute to the existing knowledge in the field and provide a comprehensive understanding of the topic.

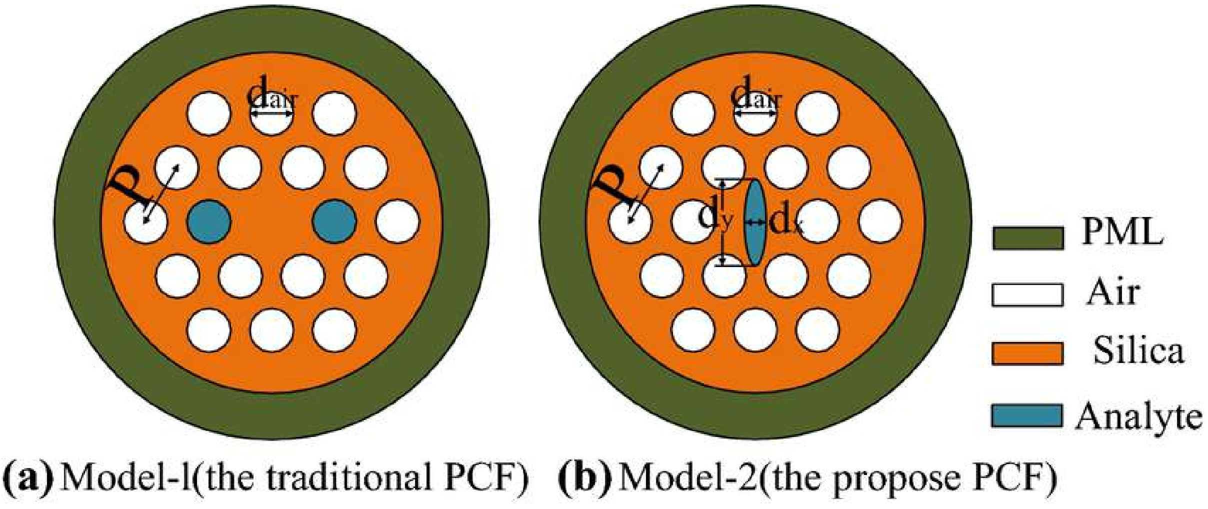
The objectives of this work are:

- To design and optimize a topas based anti-resonant hollow core fiber with low confinement loss and material loss for the efficient guidance of THz waves.
- To simulate the design to obtain various desirable modal characteristics of the fiber.
- To compare the obtained results with other simulation and experimental works.

Chapter 2
Literature Review

2.1 Conventional Optical Fiber

Conventional optical fiber has higher loss compared to some other types of optical fibers, such as photonic crystal fibers or hollow core fibers. This is because conventional optical fibers have a solid core made of silica glass, which has a higher refractive index than the surrounding cladding material, typically made of silica glass as well. As a result, when light travels through the fiber, it experiences some level of attenuation due to various factors such as absorption, scattering, and bending losses.



(a) Model-l(the traditional PCF) **(b)** Model-2(the propose PCF)

Figure 2. 1 :Conventional optical Fiber as per ref. [48]

However, it's important to note that the loss in conventional optical fibers is still relatively low, typically in the range of 0.2-0.5 dB/km for single-mode fibers and higher for multimode fibers. This level of loss is acceptable for most applications, including telecommunications, data transmission, and sensing. Furthermore, advancements in fiber optic technology, such as improved materials and manufacturing techniques, have led to lower loss in conventional optical fibers. For instance, specialized dopants can be added to the fiber core to reduce the level of absorption loss, and advanced cladding designs can reduce bending losses.

Overall, while conventional optical fiber may have higher loss compared to some other types of fibers, it is still a highly efficient and reliable means of transmitting light over long distances

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2.2 Metal Coated PCF

Metal-coated Photonic Crystal Fiber (PCF) is a type of optical fiber that has a thin layer of metal [8], such as gold or silver, deposited onto the surface of the PCF. This metal coating can modify the properties of the fiber, such as the transmission characteristics, polarization dependence, and refractive index.

The metal coating on the PCF can create a surface plasmon resonance effect, which enhances the interaction between light and the metal surface. This effect can be used to create sensors for detecting small changes in the refractive index of the surrounding environment, such as changes in temperature or the presence of certain chemicals.

In addition, the metal coating can also modify the transmission characteristics of the fiber by changing the refractive index of the cladding material. This can be used to create fiber optic devices such as filters, polarizers, and mode converters.

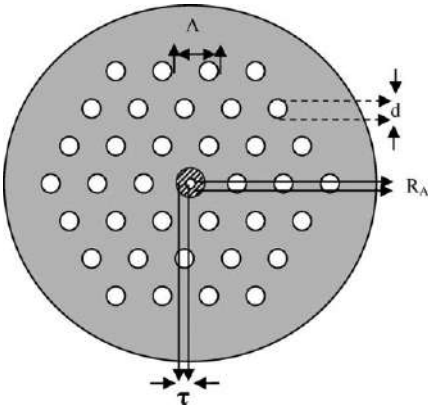


Figure 2. 2: Metal Coated PCF, ref [8]

Metal-coated PCF has several advantages over conventional solid-core fibers. The large surface area of the PCF allows for a high sensitivity in sensing applications, and the flexible nature of the PCF allows for easy integration into complex optical systems. Furthermore, the metal coating can provide additional mechanical protection to the fiber, making it more durable in harsh environments [23-24].

However, the metal coating can also introduce additional loss to the fiber, particularly at higher frequencies. Major Limitation includes Finite conductivity, Surface roughness, Unguided beam spreading. Additionally, the metal coating can be sensitive to environmental factors such as humidity and temperature, which can affect the stability of the sensor or device.

2.3 Kagome Hollow Fiber

Kagome Hollow Fiber is a type of Photonic Crystal Fiber (PCF) that has a distinctive lattice structure resembling the traditional Japanese basket called Kagome. The Kagome lattice consists of a series of interconnected triangles, forming a hexagonal pattern that can be used to create a hollow core within the fiber.

The hollow core of the Kagome Hollow Fiber provides several advantages [11] over conventional solid-core fibers, such as lower nonlinearities, higher power handling capabilities, and reduced dispersion. The structure of the fiber also allows for greater flexibility in the design of fiber optic devices, such as sensors and lasers.

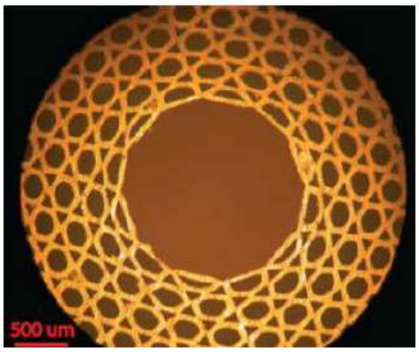


Figure 2. 3 : Kagome Hollow Fiber, ref [25]

One of the key features of the Kagome Hollow Fiber is its ability to guide light within the hollow core through a phenomenon called the inhibited coupling effect. This effect arises due to the presence of air holes surrounding the hollow core, which create a boundary that prevents light from escaping the core. As a result, the light is confined within the core, allowing for low-loss transmission and efficient coupling with other fibers or devices.

Kagome Hollow Fiber has a wide range of applications in areas such as telecommunications, sensing, and high-power lasers[25]. For example, it can be used to create compact and efficient fiber optic sensors for measuring temperature, pressure, and strain. It can also be used to generate and transmit high-power laser beams for cutting, welding, and machining.

2.4 Antiresonant Fiber

Anti-Resonant Fiber (ARF) is a type of optical fiber that has a unique structure designed to minimize the loss of light within the fiber. The fiber consists of a central core surrounded by a series of thin-walled tubes or channels, which are arranged in a periodic lattice structure. The tubes are typically made of silica or another low-index material, while the core is made of a high-index material.

The lattice structure of the tubes creates a series of anti-resonant reflecting waveguides (ARRWs) that allow light to be confined within the core of the fiber. When light encounters the periodic structure of the ARF, it undergoes multiple reflections and refractions, leading to destructive interference and reduced coupling between the core and the cladding. As a result, the fiber has lower loss and lower dispersion than conventional optical fibers.

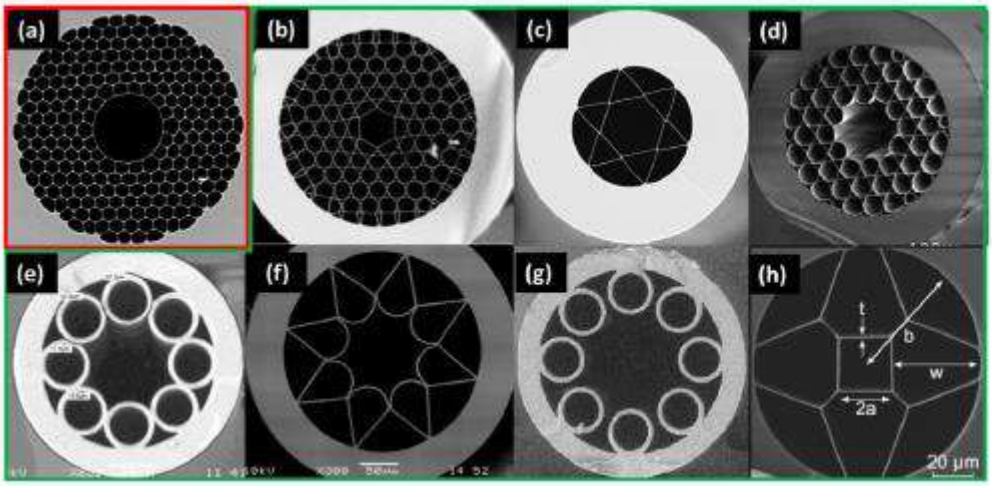


Figure 2. 4:4: Scanning Electron Micrographs (SEMs) of some representative hollow core fibers: (a) PBGF (b-h) ARFs., adapted from ref [22]

ARF has several advantages over conventional optical fibers, including high modal confinement, low loss, and low dispersion. These properties make it suitable for applications such as fiber lasers, high-power transmission, and sensing. In addition, the lattice structure of ARF can be designed to create specific modal properties, such as polarization-maintaining or single-mode operation.

2.5 Benefits of Choosing Antiresonant Fiber

Comparing anti-resonant fiber (ARF) to traditional optical fibers, there are various advantages. In contrast to typical optical fibers, ARF has a special structure that permits light to be contained within the fiber's core, resulting in lesser loss. Anti-resonant fiber is appropriate for high-speed data transmission over long distances because it has a compact core and a special lattice structure that reduces dispersion. ARF's distinctive lattice structure offers a high level of modal confinement, making it suited for fiber lasers and high-power transmission. ARF is a versatile fiber for a variety of applications because it may be made to have specific modal features, such as polarization-maintaining or single-mode operation. ARF's low-index tubes create a physical barrier that shields the core from outside influences like temperature and pressure variations, improving stability and dependability. ARF has the potential to be shrunk because it is feasible to construct it with a small diameter, making it appropriate for compact optical systems and devices [32].

ARF, compared to standard optical fibers, offers reduced loss, higher modal confinement, and greater flexibility, which has the potential to revolutionize the world of optical fiber communications and sensing.

Chapter 3

Terahertz Waveguide Materials

3.1 Introduction

Terahertz waveguides are objects that direct terahertz waves in a certain direction. To do this, a material that is transparent to terahertz radiation and can confine the radiation to a small area must be used to create the waveguide. There are several materials that can be used for terahertz waveguides, including Silicon, Polymers, Metal waveguides, Dielectrics, Photonic crystal waveguides etc [37].

3.2 Polymethylmethacrylate or PMMA

Polymethylmethacrylate, also known as PMMA or acrylic glass, is a transparent thermoplastic material that is widely used in various applications, including in construction, automotive parts, medical implants, and optical devices [44].

Polymethylmethacrylate (PMMA) is commonly used as a core material in optical fibers due to its excellent optical properties. The core of an optical fiber is the central part of the fiber that carries the light signal, and it must be made of a material with a high refractive index to ensure efficient transmission of light.

Table 3. 1: Properties of PMMA as per ref [43]

Density (g/cm^3)	1.18
Surface Hardness	RM92
Tensile Strength (MPa)	70
Flexural Modulus (GPa)	2.9
Notched Izod (kJ/m)	0.02
Linear expansion (/°C x 10^{-5})	7
Elongation at Break (%)	2.5
Strain at Yield (%)	N/A
Max. Operating Temp. (°C)	50

Water Absorption (%)	0.3
Oxygen Index (%)	19
Flammability UL94	HB
Volume Resistivity (log ohm.cm)	15
Dielectric Strength (MV/m)	25
Dissipation Factor 1kHz	0.03
Dielectric const. 1kHz	3.3
HDT @ 0.45 MPa (°C)	103
HDT @ 1.80 MPa (°C)	95
Material. Drying hrs @ (°C)	2 @ 75
Melting Temp. Range (°C)	220 - 240
Mould Shrinkage (%)	0.6
Mould Temp. Range (°C)	60 - 80

3.3 Advantages and Disadvantages of PMMA

PMMA has a high refractive index, which means it can efficiently transmit light through an optical fiber. In addition, PMMA has low attenuation, meaning that the light signal can travel long distances through the fiber without significant loss of signal strength.

PMMA optical fibers are used in various applications, including communication networks, medical equipment, and lighting. They are particularly useful in applications where flexibility is required, as PMMA fibers are more flexible than other types of optical fibers[27].

However, PMMA optical fibers also have some limitations [28]. They are more susceptible to damage from bending and physical stress than other types of fibers, and they have a lower bandwidth than some other materials, meaning that they may not be suitable for some high-speed communication applications.

Overall, PMMA is a commonly used material for optical fibers due to its excellent optical properties, but its limitations must be taken into account when considering its use in specific applications.

3.4 High Density Polyethylene of HDPE

High density polyethylene (HDPE) is a thermoplastic polymer [45] that is commonly used as a sheathing material in optical fiber cables. The sheathing of an optical fiber cable is the protective outer layer that encases the fiber and provides mechanical protection against environmental factors such as moisture, chemicals, and physical damage.

HDPE is a popular choice for optical fiber cable sheathing [29-30] because of its excellent properties, including high tensile strength, low coefficient of friction, good chemical resistance, and low moisture absorption. These properties make HDPE an ideal material for protecting the delicate optical fiber inside the cable.

In addition, HDPE is a cost-effective material that is easy to manufacture and process. It can be extruded into a variety of shapes and sizes, and it is available in a range of colors to facilitate identification and installation.

Table 3. 2 Properties of HDPE as per [45]

Density (g/cm^3)	0.96
Surface Hardness	SD68
Tensile Strength (MPa)	30
Flexural Modulus (GPa)	1.25
Notched Izod (kJ/m)	0.15
Linear Expansion (/°C x 10^{-5})	12
Elongation at Break (%)	100
Strain at Yield (%)	12
Max. Operating Temp. (°C)	55
Water Absorption (%)	0.02
Oxygen Index (%)	17
Flammability UL94	HB
Volume Resistivity (log ohm.cm)	17
Dielectric Strength (MV/m)	21
Dissipation Factor 1kHz	0.001

Dielectric Constant 1kHz	2.5
HDT @ 0.45 MPa (°C)	75
HDT @ 1.80 MPa (°C)	46
Material. Drying hrs @ (°C)	NA
Melting Temp. Range (°C)	220 - 310
Mould Shrinkage (%)	3
Mould Temp. Range (°C)	30 - 70

3.5 Limitation of HDPE

HDPE sheathing also has some limitations, such as low resistance to UV radiation and poor resistance to high temperatures, which can cause the material to become brittle and crack over time. To mitigate these limitations, HDPE can be blended with other materials, such as carbon black or antioxidants, to improve its durability and resistance to environmental factors.

Overall, HDPE is a commonly used material for optical fiber cable sheathing due to its excellent properties and cost-effectiveness, and it is a good choice for many applications where protection and durability are important considerations.

3.7 Teflon

Teflon, commonly known as polytetrafluoroethylene (PTFE), has been applied in a variety of ways to optical fiber optimization. Here are a few instances: Teflon is a good coating material for optical fibers because it increases their mechanical strength and shields them from damaging elements like moisture and abrasion. Teflon coatings can also be utilized to change a fiber's surface characteristics, such as making them hydrophobic.

Teflon is a substance with an extremely low refractive index, which makes it suitable for use as an optical fiber cladding. Teflon cladding can be used to lower a fiber's mode field diameter, which can enhance performance in some nonlinear optics applications. Teflon is a material that can be used to make the cladding for hollow core fibers, which have potential uses in spectroscopy, telecommunications, and sensing. By limiting the overlap between the guided mode and the cladding material, Teflon's low refractive index can aid in lowering the loss in these fibers.

Table 3. 3 : Properties of teflon as per ref. [46]

Density (g/cm^3)	2.15
Surface Hardness	SD63
Tensile Strength (MPa)	25
Flexural Modulus (GPa)	0.70
Notched Izod (kJ/m)	0.16
Linear Expansion (/°C x 10^{-5})	15
Elongation at Break (%)	400
Strain at Yield (%)	70
Max. Operating Temp. (°C)	180
Water Absorption (%)	0.01
Oxygen Index (%)	95
Flammability UL94	V0
Volume Resistivity (log ohm.cm)	18
Dielectric Strength (MV/m)	45
Dissipation Factor 1 kHz	0.0001
Dielectric Constant 1 kHz	2.1
HDT @ 0.45 MPa (°C)	121
HDT @ 1.80 MPa (°C)	54
Material. Drying hrs @ (°C)	NA
Melting Temp. Range (°C)	NA
Mould Shrinkage (%)	NA
Mould Temp. Range (°C)	NA

Teflon is a material that can be utilized for the microstructured cladding in microstructured fibers, which have potential uses in optical signal processing and sensing. The guided mode can be contained in the core region of the fiber by the microstructured cladding, which can be designed to change the dispersion characteristics of the fiber.

3.9 Topas

A brand of cyclic olefin copolymers (COCs) known as Topas have been utilized to make anti-resonant fibers (ARFs)[42] .

Table 3. 4 : Properties of Topas as per ref [47]

Specific gravity (gm/cc)	3.55
Water absorption (24 h immersion in water at 23 °C)	<0.01
Light transmittance (2 mm wall thickness)	91
Refractive index	1.53
Heat distortion temperature (°C)	75
Dielectric loss tangent	0.0003
Dielectric constant	2.19
Tensile strength (MPa)	63
Density (kg/m^3)	1010
Glass transition temperature (°C)	78
Deflection Temperature at 0.46 MPa	150 °C
Deflection Temperature at 1.8 MPa	135 °C

Topas COCs have several desirable qualities for ARF applications, such as:

i) Low optical loss: Topas COCs are well suited for usage in ARFs that demand low loss and good transmission because to their low optical loss over a broad wavelength range.

ii) High refractive index: Topas COCs have a high refractive index, which helps to enlarge the mode field diameter and enhance guided mode confinement in the ARF core.

iii) Low birefringence: Topas COCs are suitable for applications that call for polarization-maintaining fibers or those are sensitive to polarization effects because of their low birefringence.

iv) High thermal stability: Topas COCs are well suited for usage in high-temperature applications because of their strong thermal stability.

v) Chemical resistance: Topas COCs are effective in hostile situations since they are chemically resistant to a variety of solvents and chemicals.

3.12 Conclusion

Topas COCs feature a variety of desirable qualities that enable the manufacturing of ARFs to take use of them. For our anti resonant fiber model, we have used topas as Terahertz waveguide material. The choice of waveguide material depends on a number of factors, including the required performance specifications, the operating conditions, the fabrication process, and the cost.

Chapter 4

Theoretical Analysis of Thz Fibers

4.1 Introduction

A new family of fibers called terahertz (THz) fibers allows electromagnetic waves to travel at frequencies between 0.1 and 10 terahertz. THz radiation is used in a variety of industries, including communication, security screening, and biological imaging. THz fibers are essential in these applications because they allow for the low-loss and effective transmission of THz radiation.

Modeling the behavior of electromagnetic waves inside the fiber and comprehending the variables influencing their propagation characteristics are key components of theoretical study of THz fibers. For the design and improvement of THz fibers for many applications, this understanding is essential.

4.2 Wave Propagation

Maxwell's equations in the most general form are given in M K S units as follows:

$$\nabla . \boldsymbol{D}(r,t) = 0 \tag{4.1}$$

$$\nabla . \boldsymbol{B}(r,t) = 0 \tag{4.2}$$

$$\nabla \times \boldsymbol{E}(r,t) = -\frac{\partial \boldsymbol{B}(\mathrm{r,t})}{\partial \mathrm{t}} \tag{4.3}$$

$$\nabla \times \boldsymbol{H}(r,t) = \frac{\partial \boldsymbol{D}(\mathrm{r,t})}{\partial \mathrm{t}} \tag{4.4}$$

The standard notations for the electric field (E), the magnetic field (H), the electric displacement (D), and the magnetic induction (B) are used in these equations.

Maxwell's equations can be used to model the propagation of THz waves in fibers. These equations describe how the electric and magnetic fields behave within the fiber, and the wave equation can be solved to determine how the wave propagates. The refractive index, dispersion, and absorption of the fiber in THz fibers affect the wave propagation.

4.3 Finite Element Method

The Finite Element Method (FEM) is a numerical method for solving complicated mathematical problems that are difficult or impossible to answer analytically. These issues are often connected to engineering and physics. A large problem is divided into smaller, simpler components in FEM, and each part is then solved using a numerical technique. After then, the findings are merged to produce a general problem-solving strategy.

Partially Differential Equations (PDEs) are employed in a variety of disciplines, such as structural mechanics, fluid dynamics, heat transport, and electromagnetics, and the FEM has grown to be a popular method for their solution. The approach relies on the variational calculus principle, which entails reducing the system's overall energy.

In FEM, the problem domain is discretized into more manageable components like triangles or quadrilaterals in 2D and tetrahedra or hexahedra in 3D. Each element is represented as a collection of nodes, and piecewise continuous functions defined over these nodes are used to approximate the solution to the issue. The continuous functions are chosen to be continuous at the element boundaries and to fulfill the governing equations within each of the elements.

Discreteization, interpolation, and assembly are the three main phases of the FEM. The discretization stage establishes the nodal positions and connections while also breaking down the problem domain into smaller components. The continuous functions are roughly approximated during the interpolation step by interpolating values at the nodes. The element equations are joined in the assembly process to create the whole system of equations.

After the equations are determined, the system of equations can be numerically solved using a variety of methods, such as direct or iterative solvers. Increasing the number of elements, shifting the order of the interpolation algorithms, or applying adaptive mesh refinement techniques can all increase the accuracy of the FEM solution.

Overall, the FEM is a robust and adaptable numerical technique that has completely changed the way engineering and physics are studied. Complex issues that are impossible to solve analytically can now be resolved quickly and precisely. The optical mode analysis is made on a cross-section in the x-y plane of the fiber. The wave propagates in the z- direction and has the form

$$\bar{H}\,(x, y, z, t) = \bar{H}\,(x,y)e^{j(\omega t-\beta z)} \qquad 4.5$$

where ω is the angular frequency and β the propagation constant. An eigenvalue equation

for the magnetic field, $\bar{H}$ is derived from Helmholtz equation

$$\nabla\times(n^{-2}\nabla\times\bar{H}) - k_o{}^2\bar{H} = 0 \qquad 4.6$$

which is solved for the eigenvalue $\lambda = -j\beta$.
As boundary condition along the outside of the cladding, the magnetic field is set to zero. As the amplitude of the field decays rapidly as a function of the radius of the cladding this is a valid boundary condition.

4.4 Effective Refractive Index

An essential characteristic parameter of optical fibers, particularly for single-mode fibers, is the effective refractive index, sometimes known as the effective index. It represents the average refractive index that the guided mode in the fiber experiences.

A fiber's central core, which has a greater refractive index than the cladding around it, is where light is directed throughout the fiber. The ratio of the phase velocity of light in vacuum to the phase velocity of light in the fiber is known as the effective refractive index. It has the following mathematical expression:

$$n_{\text{eff}} = \frac{c}{v} \qquad 4.7$$

where c is the speed of light in a vacuum, neff is the effective refractive index, and v is the phase velocity of the guided mode in the fiber.

The numerical aperture of the fiber, the refractive indices of the core and cladding materials, the core diameter, and other variables all affect the effective refractive index. It typically has a refractive index that is lower than the core and higher than the cladding.

The guided mode's propagation characteristics, such as its mode field diameter and the cutoff wavelength for single-mode operation, are determined by the effective refractive index, which is significant.

4.5 Effective Refractive Index for Anti-Resonant Fiber

The effective refractive index is defined differently in anti-resonant fibers (ARFs) than it is in conventional optical fibers. Instead of entire internal reflection occurring within the core, the guiding mechanism of ARFs relies on the anti-resonant reflection of light at the cladding-air interfaces [31].

The ratio of the guided mode's propagation constant to the vacuum wave number is known as the effective refractive index in ARFs. It has the following mathematical expression:

$$n_{eff} = \frac{\beta}{k0} \qquad 4.8$$

where k_0 is the vacuum wave number, is the guided mode's propagation constant, and n_{eff} is the effective refractive index.

In ARFs, the cladding is made up of a periodic grid of air holes that together form a photonic bandgap. This bandgap prevents light from traveling through the cladding and confines the guided mode to the core. The structural characteristics of the cladding, such as the size, shape, and spacing of the air holes, affect the effective refractive index in ARFs.

In contrast to conventional optical fibers, the effective refractive index in ARFs has the potential to be lower than the cladding's refractive index. This is due to the guided mode in ARFs being constrained by the photonic bandgap in the cladding rather than complete internal reflection [32].

The guided mode's propagation characteristics, including its mode field diameter and the cutoff wavelength for single-mode operation, are greatly influenced by the effective refractive index in ARFs. Additionally, it is utilized in the development and evaluation of ARF-based devices such sensors, lasers, and amplifiers.

4.6 Effective Material Loss

Optical fibers known as anti-resonant fibers (ARF) are constructed using an optical waveguide construction that lessens light transmission in a variety of frequencies. The amount of material loss that can be tolerated in a fiber without compromising its anti-resonant characteristics is referred to as effective material loss in ARFs.

By using pure silica as the fiber's core and cladding materials, effective material loss in ARFs can be reduced. Such materials have low absorption and scattering capabilities. In order to lessen the effect of material loss on its anti-resonant capabilities, the fiber's design can also be improved, including the size of the core, the thickness of the cladding, and the number of anti-resonant features.

In order to prevent introducing flaws or damage that could increase absorption or dispersion, effective material loss can also be reduced through careful production and handling of the fiber. This includes regulating the temperature and humidity throughout the fabrication process as well as abstaining from stretching or twisting the fiber beyond what is allowed.

In THz light propagation, one of the most significant loss parameters is material loss or absorption loss. EML can be expressed as –

$$\alpha_{EML} = 4.34\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{\int_{A_{mat}} \eta\alpha_{mat}|E|^2 dA}{\int_{All} S_z dA}. \qquad 4.9$$

Here, ε_0 and μ_0 are the free space permittivity and permeability, respectively, η and α_{mat} represent the refractive index and absorption of Topas material, respectively. Sz is the z-component pointing vector.

Effective material loss is a crucial factor to take into account when designing and manufacturing ARFs since it has an effect on the anti-resonant characteristics of the fiber and how well it performs in optical applications.

4.7 Confinement Loss

ARF is characterized by confinement loss, or the quantity of light lost as a result of the fiber's structural layout. Concealment loss in ARF happens when light seeps into the surrounding cladding from the fiber's core, weakening the overall signal.

Depending on the particular design and usage circumstances, ARF confinement loss can change. ARF, on the other hand, can typically achieve extremely low confinement losses, which makes them suitable for high-performance applications that call for little signal attenuation.

The capacity of ARF to produce minimal loss at particular wavelengths, which makes them suitable for filtering applications, is one of their main advantages. ARF is advantageous for uses like broadband sensing and telecommunications since it can also demonstrate low loss over a wide variety of wavelengths.

Confinement Loss (CL) or leakage loss can be estimated from this formula,

$$\text{CL}= \frac{8.686\times 2\pi f\times Im\left(n_{eff}\right)}{c} \qquad 4.10$$

n_{eff} is the imaginary part of effective refractive index, f is the applied frequency and c is the velocity of light.

ARFs are an invaluable tool for a range of optical applications due to their distinctive architecture, which enables them to achieve extremely low confinement losses.

4.8 Dispersion

In optical fibers, dispersion is a crucial parameter that can impact the effectiveness of signal transmission. Dispersion in anti-resonant fibers (ARFs) is principally governed by the fiber's geometry and refractive index profile.

ARFs have a distinctive design that features a central core encircled by a cladding layer with a number of air holes placed in a certain pattern. These air holes produce a photonic bandgap that can block out particular wavelengths or frequency bands.

Group velocity dispersion (β_2) can be found from expression below –

$$\beta_2 = \frac{d\eta_{eff}}{d\omega}\frac{2}{c} + \frac{\omega}{c}\frac{d^2\,\eta_{eff}}{d^2\omega} \qquad 4.11$$

ω , c and η_{eff} orderly represent angular velocity, light speed and effect refractive index.

The geometry of the fiber, particularly the size and spacing of the air pores in the cladding layer, affects the dispersion characteristics of ARFs. ARFs can generally display both normal and anomalous dispersion depending on the precise design and operating circumstances.

Shorter wavelengths propagate more quickly than longer ones in normal dispersion, whereas the reverse is true in anomalous dispersion. The size and spacing of the air pores in the cladding layer can be changed to alter the dispersion properties of ARFs.

Third-order dispersion and higher-order dispersion are examples of higher-order dispersion effects that ARFs can display. These impacts may limit the fiber's bandwidth and cause signal distortion. To attain the best performance for a particular application, these effects can be reduced or managed by carefully designing the fiber structure.

Overall, the fiber geometry governs the dispersion characteristics of ARFs and can be managed by careful design and optimization. ARFs can be customized for a range of applications, including sensing, laser delivery, and telecommunications, by controlling the dispersion properties.

4.9 Bending Loss

An anti-resonant fiber's (ARF) bending radius is influenced by a number of variables, including the fiber's diameter, composition, and cladding type. ARFs are often more resistant to bending-induced losses than traditional single-mode fibers because they have a larger bending radius[18].

Depending on the precise design and production of the fiber, the bending radius of an ARF can change. To avoid excessive bending losses, it is advised, as a general rule, to choose a bending radius that is at least 10 times the fiber diameter. The curvature dependent bending loss starts with the transition of curvature radii from zero (and infinite for straight fiber) to finite (for bent fiber).

The bending of straight fiber towards x-plane makes the fiber bent and deforms the fundamental air-core index profile LP_{01} towards the cladding tube. This deformation of index profile towards the cladding tube enhances the confinement loss as compared to straight fiber. The air-core index profile for the bent fiber, $\eta_{bend(x)}$ is quantified using the equation,

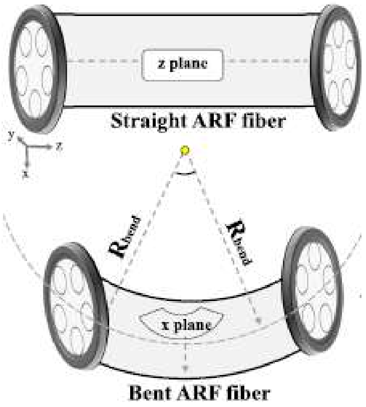


Figure 4. 1: Symbolic representation of straight and bent ARF [49]

$$\eta_{bend}(x) = \eta(x)e^{x/R_{bend}} \quad 4.12$$

where $\eta(x)$ denotes a refractive index profile of straight fiber. In simulation, we use $\eta(x) = 1$. Here, x is the bending direction and R_{bend} defines the bend radius.

4.10 Normalized frequency of V-parameter:

The following equation [43] computes normalized frequency or V-parameter to determine if the fiber works at single-mode or multi-mode.

$$V = \frac{2\pi r f}{c}\sqrt{{n_{co}}^2 - {n_{cl}}^2} \leq 2.405 \quad 4.13$$

where n_{co} and n_{cl} are the refractive indices of the fiber core and cladding, respectively, and r is the radius of the core, f is the operating frequency, and c is the speed of light in free space. n_{co} is thought to be close to 1. This is because core primarily consists of air and n_{cl} is regarded as n_{eff} because the cladding has both material and air holes. The value of the V-parameter must be equal to or less than 2.405 in order to retain single mode functioning.

4.11 Conclusion

These many types of losses together make up an ARF's overall loss, and the best way to build an ARF for a given application and set of performance requirements. In general, ARFs are well suited for high-performance applications that demand little signal attenuation because they can achieve very low loss over a wide range of wavelengths.

Overall, confinement loss, bend loss, scattering loss, and absorption loss all contribute to the loss attributes of ARFs and can be improved by careful design and material selection.

Chapter 5

Proposed Models and Simulation Results

5.1 Introduction

We will talk about our proposed models in this chapter, along with the outcomes of their simulations. Additionally, we will plot various frequencies and core lengths against parameters like effective index, effective material loss, confinement loss, dispersion, and birefringence. Finally, we will compare our model to other recent models that different research teams have developed.

5.2 Proposed Structure

We have designed four models for our work and proposed internally nested Hollow Core Anti Resonant Fiber for their unique properties in Thz light propagation.

We have used COMSOL Multiphysics 5.6, a software platform for simulating and modeling physics-based systems and processes. It provides a user-friendly interface for creating, solving, and analysing complex mathematical models of physical phenomena. The platform uses finite element analysis (FEA) methods to solve problems across a wide range of physics disciplines.

We have used Matlab 2021 for plotting the loss parameters for different frequencies. We have used core diameter $D_c = 3$ mm, outer shell diameter $D = 2.1$ mm, thickness $t = 0.09$ mm, inner circle diameter $d = 0.54$ mm, middle circle diameter $d_2 = 1.6$ mm.

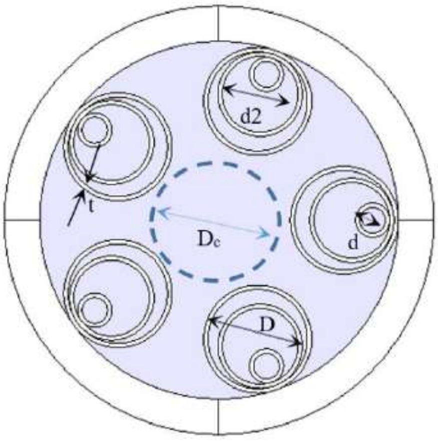


Figure 5.1

Figure 5. 1 : Cross Section of Proposed internally nested HC-Anti resonant Model

5.3 Design Optimization

An essential stage in creating anti-resonant fibers (ARFs) that satisfy particular performance criteria is design optimization. The cladding is a crucial part of ARFs, and the way it is designed greatly affects the characteristics of the fiber. To achieve particular performance objectives, such as limiting bending loss or improving dispersion properties, the size, shape, and spacing of the air holes in the cladding can be tuned. In order to meet particular performance objectives, such as enlarging the mode field or decreasing confinement loss, the core of an ARF can also be modified. It is possible to modify the core's refractive index profile to obtain particular qualities, such as mode coupling or dispersion characteristics.

The choice of materials for the fiber can have a significant impact on its properties, including loss, dispersion, and mechanical strength. Selecting materials with low absorption, low scattering, and high mechanical strength can help optimize the performance of the fiber. To obtain the necessary performance characteristics, optimizing the design of an ARF entails a careful balancing of these and other aspects. The performance of the fiber may be predicted and different design options can be assessed with the aid of simulation tools like COMSOL Multiphysics.

5.3.1 Typical HC-ARF

A typical hollow-core anti-resonant fiber (HC ARF) is a type of optical fiber with a hollow core that is surrounded by a cladding of air holes. The air holes are arranged in a pattern that creates an anti-resonant effect, which suppresses the propagation of light in the cladding.

In our design we have used 5 Circular anti resonant tubes for the typical HC_ARF model, with core diameter $D_c = 3$ mm, outer shell diameter $D = 2.1$ mm, thickness $t = 0.09$ mm.

The HC ARF's cladding is made to produce an anti-resonant effect, which inhibits light from propagating through the cladding. A bandgap is made by the way the air holes are structured, which stops some wavelengths of light from traveling through it.

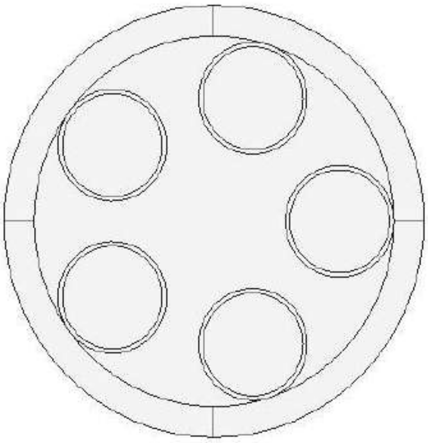


Figure 5. 2 : Typical HC-ARF

5.3.2 Nested HC-ARF

The nested HC-ARF in which a small nested tube with inner diameter, *d* is shown in Fig. 5.2. An optical fiber known as a nested hollow-core anti-resonant fiber (HC ARF) has numerous layers of nested anti-resonant claddings surrounding a central hollow core. Single circular tube has been inserted inside the outer shell tubes for better results.

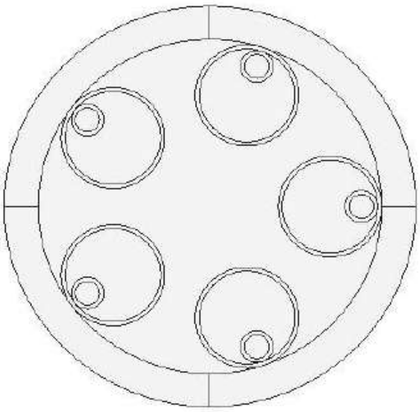


Figure 5. 3 : HC-ARF in which single nested tube

5.3.3 Double Nested HC-ARF

An optical fiber known as a double nested hollow-core anti-resonant fiber (HC ARF) has a hollow core in the centre surrounded by two layers of nested anti-resonant claddings. The optical characteristics of the fiber, such as dispersion and birefringence, can be further controlled by the double nested design, which also permits even lower losses than single nested designs.

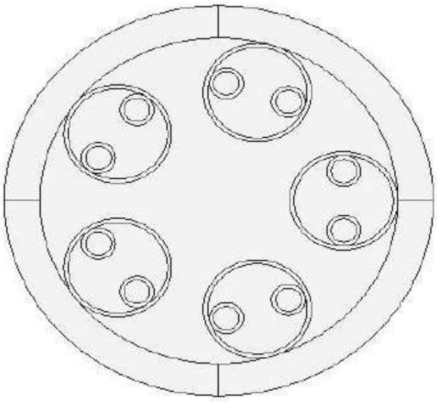


Figure 5. 4 : Double Nested HC-ARF

A double nested five-tube HC-ARF is shown in Fig. 5.3. where two adjacent nested tubes are placed in each anti resonant tube. For design simplicity we have taken symmetric circular shaped double nested circles.

5.3.4 Model design optimization for low loss properties

Numerous elements, such as the fiber's geometry, composition, and fabrication methods, have an impact on the loss characteristics of ARF. Scattering, which results from microscopic flaws in the structure of the fiber, is the main cause of loss in ARF. The presence of impurities in the fiber components, flaws in the fiber's shape, or other reasons might cause scattering. The size and distribution of the scattering centres, as well as the wavelength of the guided mode, all affect how much scattering loss occurs in ARF.

Confinement loss, which results from the interaction of the guided mode and the surrounding cladding, is another source of loss in ARF. To obtain specified optical features, such as low dispersion and high birefringence, confinement loss is purposefully added to ARFs. The size, geometry, and difference in refractive indices between the core and cladding all affect how much confinement loss occurs in ARF.

The connection of the guided mode to radiation modes as the fiber is bent or curved can also result in bending loss in ARFs. The geometry of the fiber, the bending radius, and the wavelength of the guided mode all affect how much bending loss occurs in ARF. ARFs can achieve low loss and good performance over a broad range of wavelengths by minimizing scattering and confinement loss and improving the design and materials of the fiber.

For model optimization we have considered confinement loss, effective material loss and total transmission loss. We have simulated data for 0.5 to 1.4 Thz frequency and found best results around 1 Thz and internally nested HC-ARF had the lowest transmission loss for this specific range of operational frequency.

Table 5.1 shows the total transmission loss for all four models near 01 THz frequency

Model	Frequency	Total transmission loss (dB/m)
1.Typical HC-ARF model	01 THz	0.1213
2.Single Nested HC-ARF model	01 THz	0.0950
3.Double Nested HC-ARF model	01 THz	0.0907
4.Internally nested HC-ARF model	01 THz	0.083991

Table 5. 2 shows the confinement loss, effective material loss and total transmission loss for proposed internally nested HC-ARF design.

Frequency (THz)	CL (dB/m)	EML (dB/m)	Total Tx Loss (dB/m)
0.65	6.6215	1.113991	7.735491
0.69	5.3338	0.927458	6.261258
0.71	1.3788	0.486644	1.865444
0.725	0.60407	0.264467	0.868537
0.75	0.22087	0.199757	0.420627
0.775	0.28702	0.177641	0.464661
0.8	0.18212	0.151687	0.333807

0.825	0.042661	0.122696	0.165357
0.85	0.016651	0.108591	0.125242
0.875	0.007548	0.098822	0.106369
0.9	0.007194	0.093188	0.100382
0.925	0.003284	0.088206	0.09149
0.95	0.003898	0.085055	0.088953
0.975	0.003024	0.082512	0.085536
1	0.002755	0.081236	**0.083991**
1.025	0.00409	0.081466	0.085556
1.05	0.002281	0.082	0.084281
1.075	0.003084	0.083614	0.086698
1.1	0.003457	0.08608	0.089536
1.125	0.002864	0.089235	0.092099
1.15	0.004511	0.094182	0.098693
1.175	0.004159	0.10005	0.104209
1.2	0.003522	0.107992	0.111514

5.3.5 Perfectly Matched Layer (PML)

Across computational electromagnetics, a perfectly matched layer (PML) is a method for simulating the behavior of electromagnetic waves across unbounded domains. A bounding box or border, which is a finite area that restricts the size of the simulation, surrounds a domain in many simulations. Some of the electromagnetic waves that hit the border are reflected back into the domain, leading to numerical distortions and errors.

PMLs are added as an absorbent layer at the simulation domain's edge to solve this problem. All electromagnetic waves that hit the PML are intended to be absorbed, effectively removing reflections and reducing numerical artifacts. In essence, the PML is a zone with variable permittivity and permeability that smoothly changes from the characteristics of the surrounding medium to a zone with high absorption.

The PML is frequently implemented as an additional set of Maxwell's equations, and it is solved numerically using techniques like the finite difference time domain (FDTD) or the finite element method (FEM). through computational electromagnetics simulations of antenna design, electromagnetic scattering, and wave propagation through optical fibers, the PML technique is frequently employed.

The ability to be customized to absorb particular frequencies or ranges of frequencies makes PMLs advantageous for simulations involving wideband electromagnetic fields. Additionally, PMLs can be used in both 2D and 3D simulations, and commercial software programs like COMSOL Multiphysics and MATLAB make it relatively simple to implement them.

For our design, we have selected PML and Extra fine triangular mesh for better accuracy.

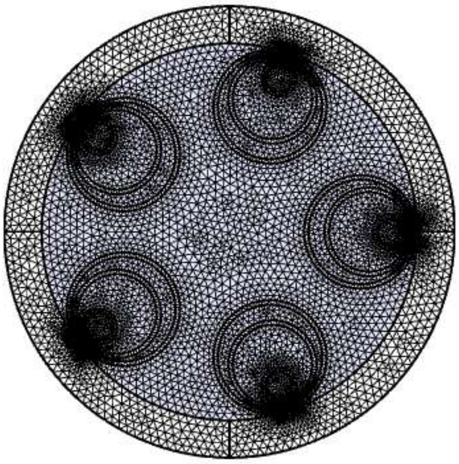


Figure 5. 5 : PML and Extra fine triangular mesh

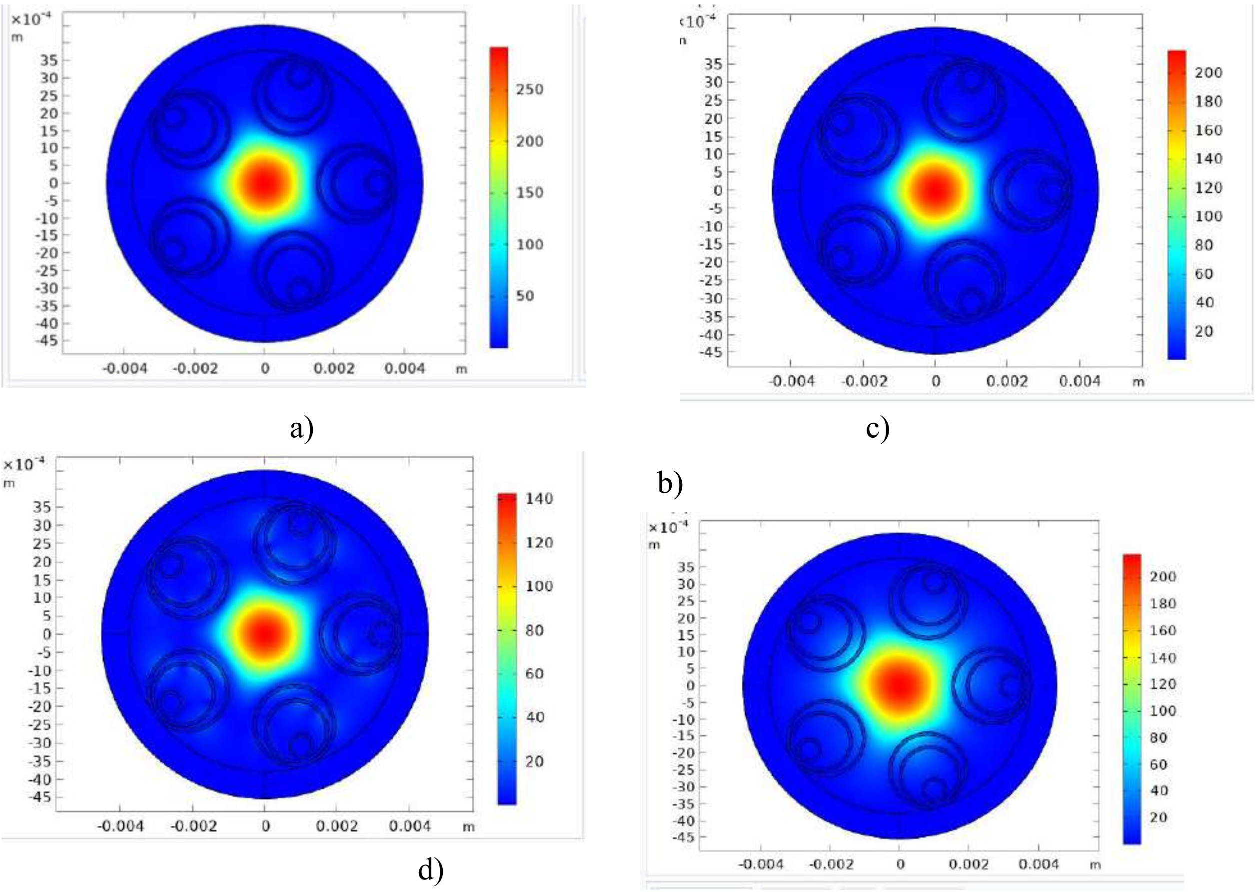
5.3.6 Light Confinement Range in Anti-Resonant Fiber

The distance from the fiber's core at which the majority of its optical power is contained is referred to as the light confinement range in an optical fiber. The light confinement range in a single-mode fiber, which only supports one guided mode, is typically between 5 and 10 microns. This indicates that a cylindrical portion of the fiber with a diameter of roughly 10–20 microns contain the majority of the optical power.

The anti-resonant cladding design of an anti-resonant fiber (ARF), which produces an anti-resonant waveguide and limits light to the fiber's core, determines the light confinement range [33]. When compared to conventional single-mode fibers, the light confinement range in ARF can be significantly larger, spanning several tens to several hundreds of microns.

The shape of the cladding, the contrast in refractive indices between the core and cladding, and the wavelength of the guided mode all have an impact on the light confinement range in ARF. A significant light confinement range in ARF can be achieved while preserving low loss and great performance over a broad range

[34] of wavelengths by carefully optimizing the cladding structure and refractive index contrast.



a)

c)

b)

d)

Figure 5. 6 Light confinement in wider frequency range

a) Frequency-1THz, EMI= 0.9971
b) Frequency-0.675THz, EMI= 0.99422
c) Frequency-0.8THz, EMI= 0.99618
d) Frequency- 1.4THz, EMI=0 .991

5.3.7 Confinement Loss

Confinement Loss (CL) or leakage loss can be estimated from this formula 4.10,

$$CL= \frac{8.686\times 2\pi f\times Im(n_{eff})}{c}$$

n_{eff} is the imaginary part of effective refractive index, f is the applied frequency and c is the velocity of light.

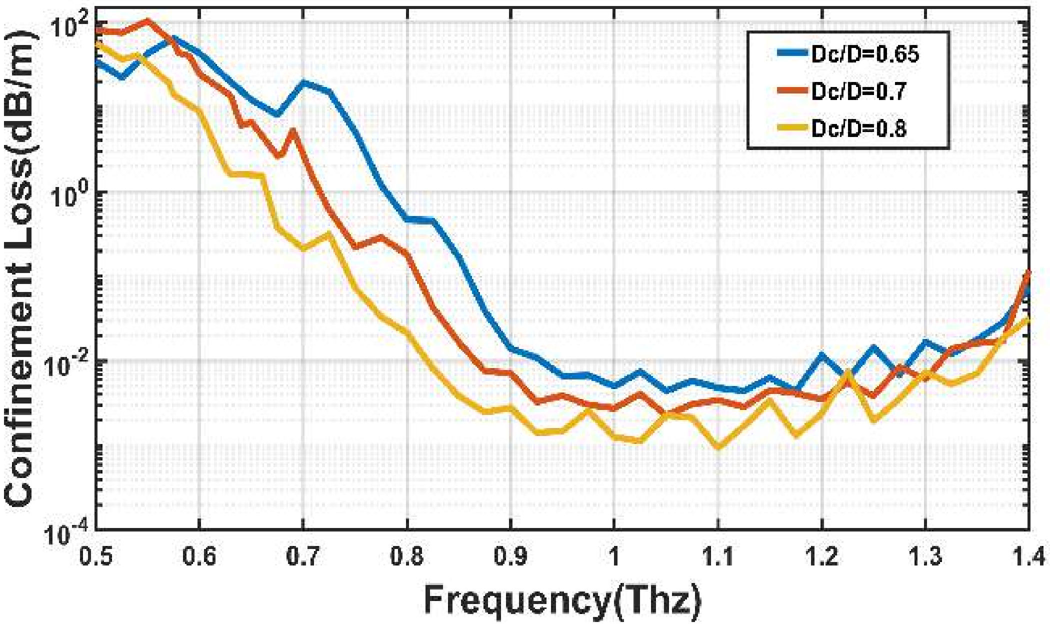


Figure 5. 7: Confinement loss for different diameter ratio ($\frac{D_C}{D} = 0.65,0.7,0.8$)

From Figure 5.7 it is observed that our internally nested HC-ARF provides very lower confinement loss compared with conventional fiber. Thus, HC-ARFs can provide low confinement loss, making them useful in applications that require high-speed data transmission or precise control of pulse shapes in fiber lasers.

Table 5. 3: Lowest Confinement loss for different diameter ratio ($\frac{D_C}{D} = 0.65,0.7,0.8$)

Dc/*D*	Lowest CL(dB/m)	Freq.(THz)
0.65	0.04395	1.175
0.65	0.0518	1
0.7	0.02281	0.075
0.7	0.02755	1
0.8	0.00094	1.1
0.8	0.000127	1

5.3.8 Effective Material loss

In THz light propagation, one of the most significant loss parameters is material loss or absorption loss. From equation 4.9 EML can be expressed as –

$$\alpha_{EML} = 4.34\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{\int_{A_{mat}}\eta\alpha_{mat}|E|^2dA}{\int_{All}S_z dA}.$$

Here, ε_0 and μ_0 are the free space permittivity and permeability, respectively, η and α_{mat} represent the refractive index and absorption of Topas material, respectively. Sz is the z-component pointing vector.

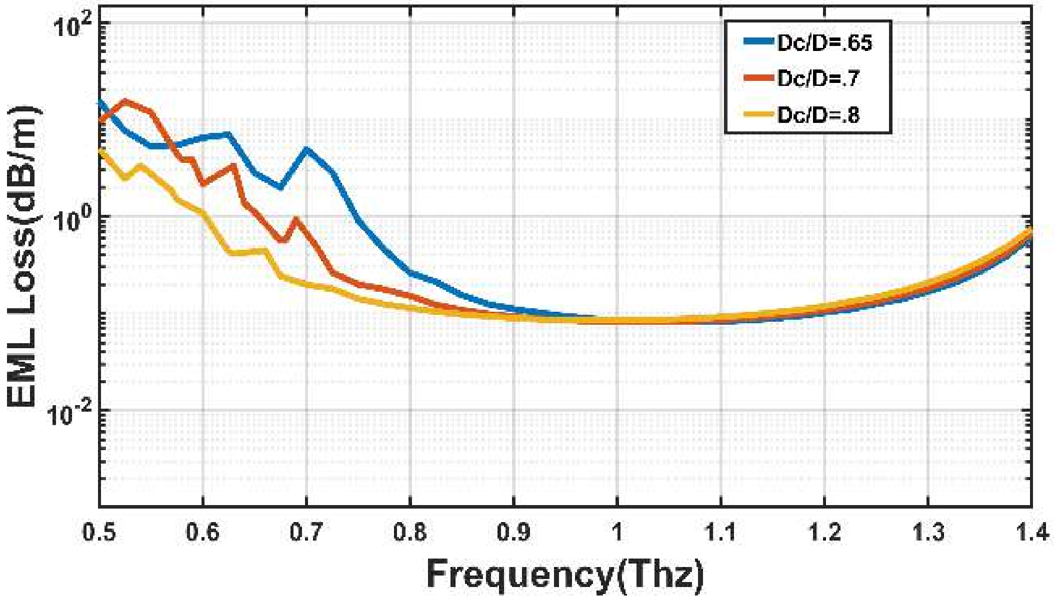


Figure 5. 8 : EML for different diameter ratio ($\frac{Dc}{D} = 0.65, 0.7, 0.8$)

From figure 5.8 it is observed that EML loss was lower near 1 THz spectrum amd through wide range of frequency EML was considerably lower.

Table 5. 4 : Lowest EML for different diameter ratio ($\frac{Dc}{D} = 0.65, 0.7, 0.8$)

Dc/*D*	Lowest EML(dB/m)	Freq.(THz)
0.65	0.081323	1.05
0.7	0.081236	1
0.8	0.08466	1

We have found lowest EML for 1Thz is 0.081236 dB/m for diameter ratio 0.7 (Dc/*D*)

5.3.8 Total Propagation Loss

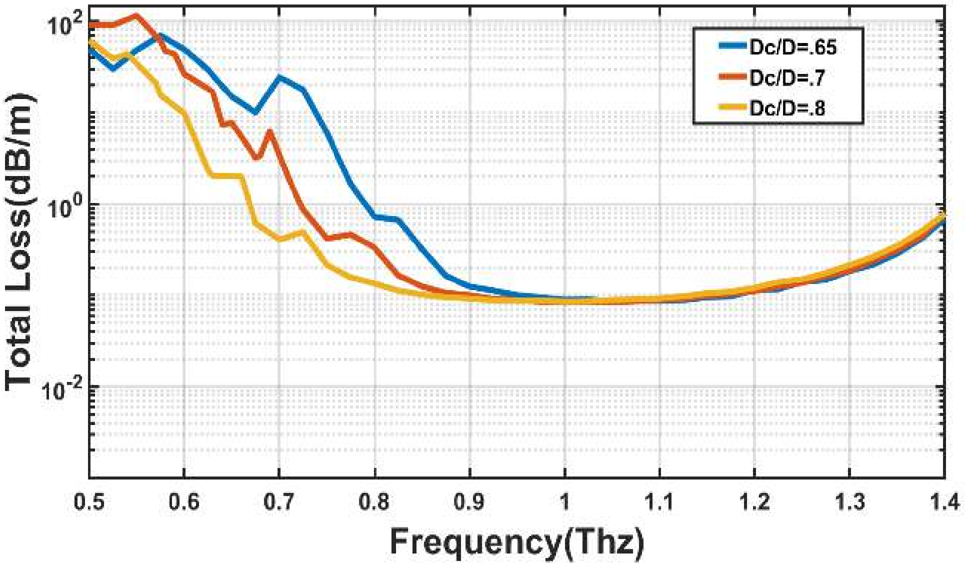


Figure 5. 9 : Total propagation loss for different diameter ratio ($\frac{D_C}{D} = 0.65,0.7,0.8$)

It is observed that in the range of 0.5 THz – 0.9 THz region, for maximum diameter ratio ($D_c/D = 0.8$) the proposed fiber has offered the minimum transmission loss properties. However, the fiber offers lower propagation loss in the range of 0.9 THz – 1.4 THz for all three diameter variations. We have found the lowest propagation loss of 0.083991 dB/m at 1 THz.

Overall, the total propagation loss in our specific design of HC-ARF will be much lower than the conventional fiber, but ARFs can generally be considered to have lower losses than conventional fibers in the THz regions.

5.3.9 Dispersion

Group velocity dispersion (β_2) can be found from expression 4.11 as –

$$\beta_2 = \frac{d\eta_{eff}}{d\omega}\frac{2}{c} + \frac{\omega}{c}\frac{d^2\,\eta_{eff}}{d^2\omega}$$

ω , c and η_{eff} orderly represent angular velocity, light speed and effect refractive index.

Figure 5.10 is showing the dispersion property for the internally adjacent nested tube anti-resonant fiber. Best dispersion properties are observed in between 0.77 THz to 1.37 THz. In this range, the value of dispersion is around 0.3 ps/THz/cm. Thus, the proposed fiber offers a very low and flat dispersion profile.

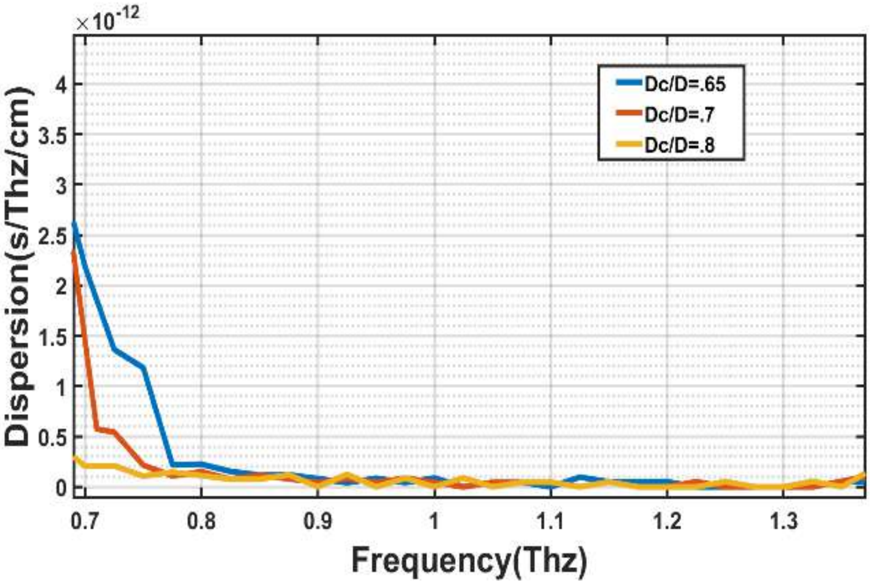


Figure 5. 10 : Dispersion for different diameter ratio ($\frac{Dc}{D} = 0.65, 0.7, 0.8$)

From figure 5.10 we are observing that that in between wider range of THz spectrum very flat dispersion profile. Our internally adjacent HC-ARF can provide low dispersion loss, making them useful in applications that require high-speed data transmission or precise control of pulse shapes in fiber lasers.

5.3.10 Bending Loss

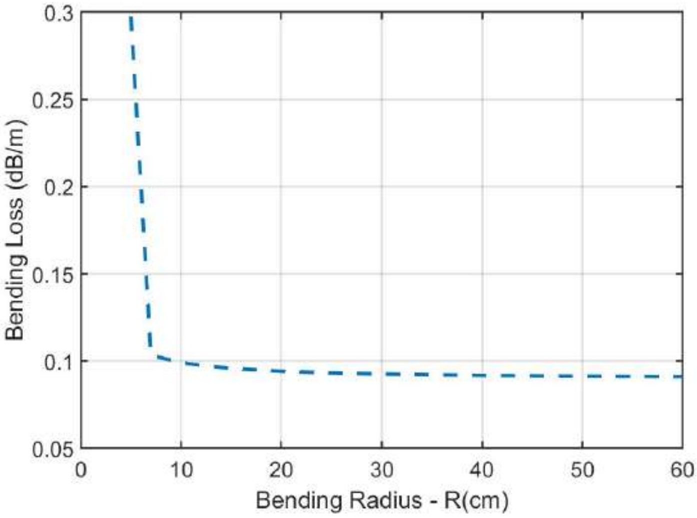


Figure 5. 11: Bending Loss

An optical fiber known as an anti-resonant fiber (ARF) employs a cladding structure that is intended to block higher-order modes and direct light in a low-index area. Due to their distinct cladding structure, which reduces bending loss, ARFs are made to have a high bend tolerance.

When ARFs are subjected to sharp bends or high curvature, they may nevertheless suffer considerable bending loss. Mode leakage from the low-index zone to the high-index region, which results in radiation loss, is what causes this bending loss.We use a range of R_{bend} values from 3 cm to 60 cm to quantitatively analyze the bend and transmission loss of bent fiber [Fig 5.11]. The bending loss of the fiber in very negligible.

In figure 5.2 We have found n_{bend} is decreasing and from 7-60cm bending radius it's reaching near round value 1.

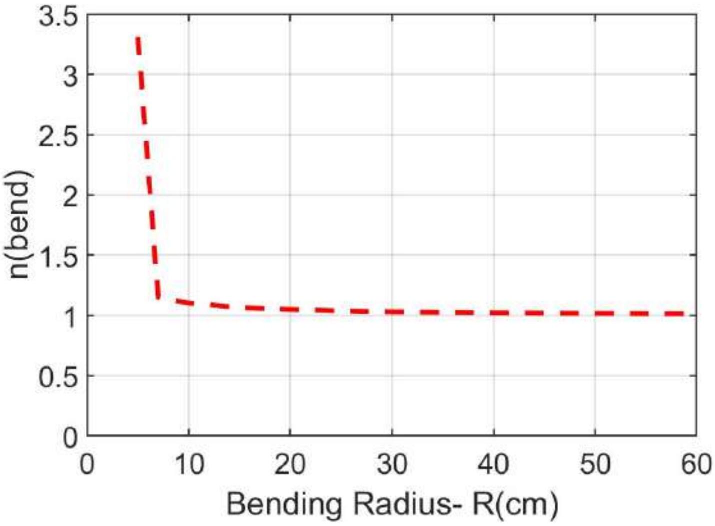


Figure 5. 12: n_{bend} with bending radius

We have used formula 4.12 for detecting bending loss and n_{bend}. . From figure 5.11 it is found that the bending loss is decreasing with increasing bending radius, which really help us to provide low bending loss characteristics.

Overall, ARFs have lower bending loss compared to conventional single-mode fibers due to their unique structure. However, it is still important to consider the bending loss when designing and using ARFs in practical applications.

5.3.11 Single Mode Detection

The modal characteristics of HC-ARFs are numerically examined in this section with a fixed Dc, while the cladding tube diameter is adjusted over a range where the HOMs are suppressed at f = 1 THz. The lowest mode, LP01, exhibits the smallest transmission loss at this frequency and has taken over as the predominant mode in HC-ARFs. The following equation [4.13] computes normalized frequency or V-parameter to determine if the fiber works at single-mode or multi-mode.

$$V = \frac{2\pi rf}{c} \sqrt{{n_{co}}^2 - {n_{cl}}^2} \leq 2.405$$

where n_{co} and n_{cl} are the refractive indices of the fiber core and cladding, respectively, and r is the radius of the core, f is the operating frequency, and c is the speed of light in free space. n_{co} is thought to be close to 1, n_{cl} is regarded as n_{eff} because the cladding has both material and air holes. The value of the V-parameter must be equal to or less than 2.405 in order to retain single mode functioning.

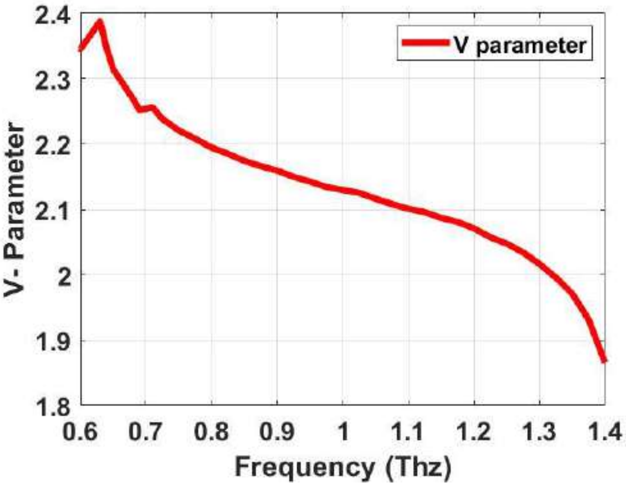


Figure 5. 13: V-Parameter from 0.6 to 1.4 THz range

Here from figure 5.13 , we are observing within 0.6 THz to 1.4Thz range V-Parameter is lower than 2.4, so this analysis detects that our fiber model is a single mode fiber. As per equation 4.11 if V-parameter is below 2.405, so we can definitely say that our internally adjacent nested HC-ARF works perfectly as single mode fiber.

5.3.12 Performance Analysis

In order to analyze the performance of hollow core anti-resonant fibers (HC-ARFs), it is common practice to measure a number of important factors, such as loss, dispersion, and mode field diameter (MFD). Low loss, particularly in the near-infrared (NIR) and mid-infrared (MIR) spectral bands, is one of the key benefits of HC-ARFs. Absorption and scattering losses, which can be reduced by employing the right materials and enhancing the fiber structure, are often the main causes of HC-ARF loss.

Another crucial factor that influences the performance of HC-ARFs is dispersion. Since they generally have low dispersion over a broad wavelength range, HC-ARFs are well suited for tasks like pulse compression and the delivery of ultrafast laser pulses.

5.13 Fabrication Feasibility

Anti-resonant fiber (ARF) fabrication typically entails a number of procedures, such as preform fabrication, fiber drawing, and post-processing. The initial stage of making an ARF is called preform fabrication [40], and it entails creating a glass or polymer preform with the necessary cladding structure. The cladding is typically placed layer by layer on the core material during the fabrication of the preform utilizing a modified chemical vapor deposition (MCVD) or a modified stack-and-draw method. We can fabricate our internally adjacent anti resonant fiber with below mentioned methods

1. Stacking
2. 3D printing
3. Extrusion (HC-ARF can be fabricated directly from the melted granules.)

The stack and drawn technique can collapse and deform the antiresoanat tube. So, 3D printing and Extrusion can be considered while fabrication of internally adjacent HC-ARF [41].

5.14 Fabrication tolerance

Anti-resonant fibers' (ARFs) fabrication tolerance is influenced by a number of variables, including the fiber's structure, its constituent parts, and its intended use. Examples of fabrication tolerances for ARFs include core diameter, cladding thickness, cladding hole size and spacing, material characteristics, and geometric tolerances. This model's loss parameters fall within a 1-5% fab tolerance.

Reference

[1] B. Ferguson and X.-C. Zhang, “Materials for terahertz science and technology,” Nature Mater., vol. 1, no. 1, pp. 26–33, Sep. 2002.

[2] M. Tonouchi,“Cutting-edge terahertz technology,” Nature Photon., vol. 1, no. 2, pp. 97–105, Feb. 2007.

[3] Fitch, M. J., and Osiander, R., “Terahertz waves for communications and sensing,” Johns Hopkins APL Tech. Dig. Applied Phys. Lab. Vol 25, pp. 348–355, 2004.

[4] D. Mittleman, Sensing With Terahertz Radiation. Cham, Switzerland:Springer, 2003.

[5] Strachan, C. J., Taday, P. F., Newnham, D. A., Gordon, K. C., Zeitler, J. A., Pepper, M., and Rades, T., "Using terahertz pulsed spectroscopy to quantify pharmaceutical polymorphism and crystallinity," J. Pharm. Sci. Vol 94, pp. 837–846, 2005.

[6] Abbott, D., and Zhang, X. C., "Scanning the issue: T-ray imaging, sensing, and retection," Proc. IEEE Vol. 95, pp. 1509–1513, 2007.

[7] Wang, K, and Mittleman, D. M., "Metal wires for terahertz waveguiding," Nature Vol. 432, pp. 376–379, 2004.

[8] Kejalakshmy, N., Rahman, B. M. A., Agrawal, A., Tanvir, H. M., and Grattan, K. T. V., "Metal-Coated Defect-Core Photonic Crystal Fiber for THz Propagation," J. Light. Technol. Vol. 27, pp. 1631–1637, 2009.

[9] L.-J. Chen, H.-W. Chen, T.-F. Kao, J.-Y. Lu, and C.-K. Sun, “Low-loss subwavelength plastic fiber for terahertz waveguiding,” Opt. Lett., vol. 31, no. 3, pp. 308–310, 2006.

[10] K. Nielsen, H. K. Rasmussen, P. U. Jepsen, and O. Bang, “Porous-core honeycomb bandgap THz fiber," Opt. Lett., vol. 36, no. 5, pp. 666668, Mar. 2011.

[11] J. Anthony, R. Leonhardt, S. G. Leon-Saval, and A. Argyros, “THz propagation in Kagome hollow-core microstructured fibers,” Opt. Express, vol. 19, no. 19, pp. 1847018478, Sep. 2011.

[12] R. Mendis and D. Grischkowsky, “Undistorted guided-wave propagation of subpicosecond terahertz pulses,” Opt. Lett. 26(11), 846–848 (2001).

[13] Sultana, J., Islam, M. S., Faisal, M., Islam, M. R., Ng, B. W. H., Ebendorff-Heidepriem, H., and Abbott, D., "Highly birefringent elliptical core photonic crystal fiber for terahertz application," Opt. Commun. Vol. 407, pp. 92–96, 2018.

[14] A. Hassani, A. Dupuis, and M. Skorobogatiy, “Low loss porous terahertz fibers containing multiple subwavelength holes,” Appl. Phys. Lett., vol. 92, no. 7, Feb. 2008, Art. no. 071101.

[15] A. Ge, F. Meng, Y. Li, B. Liu, and M. Hu, “Higher-order mode suppression antiresonant nodeless hollow-core fibers,” Micromachines 10(2), 128 (2019).

[16] G. K. M. Hasanuzzaman, S. Iezekiel, C. Markos, and M. S. Habib, “Hollow-core fiber with nested anti-resonant tubes for low-loss THz guidance,” Opt. Commun., vol. 426, pp. 477–482, Nov. 2018.

[17] P. Uebel, M. C. Günendi, M. H. Frosz, G. Ahmed, N. N. Edavalath, J.-M. Ménard, and P. S. J. Russell, “Broadband robustly single-mode hollow-core PCF by resonant filtering of higher-order modes,” Opt. Lett., vol. 41, no. 9, pp. 19611964, 2016.

[18] S.-F. Gao, Y.-Y. Wang, X.-L. Liu, W. Ding, and P. Wang, “Bending loss characterization in nodeless hollow-core anti-resonant fiber," Opt. Express, vol. 24, no. 13, pp. 1480114811, 2016.

[19] X. Fu, Y. Liu, Q. Chen, Y. Fu, T. J. Cui “Applications of Terahertz Spectroscopy in the Detection and Recognition of Substances,” Front. Phys., 12 May 2022 Sec. Optics and Photonics, Volume 10 – 2022.

[20] A. D. Pryamikov et al., “Demonstration of a waveguide regime for a silica hollow—core microstructured optical fiber with a negative curvature of the core boundary in the spectral region > 3.5 μm”, Opt. Expr. 19 (2), 1441 (2011).

[21] A. V. Gladyshev et al., “Efficient 1.9-μm Raman generation in a hydrogen-filled hollow-core fibre”, Quantum Electron. 45, 807 (2015).

[22] F. Poletti, “Nested antiresonant nodeless hollow core fiber”, Opt. Express 22 (20), 23807 (2014).

[23] M. Skorobogatiy and J. Yang, "Metal-coated photonic bandgap fibers," Journal of Lightwave Technology, vol. 23, no. 1, pp. 200-209, Jan. 2005.

[24] D. Monzón-Hernández et al., "Metal-coated photonic crystal fiber for sensing applications," Sensors and Actuators B: Chemical, vol. 169, pp. 163-169, May 2012.

[25] B. Debord et al., "Hollow-core fiber design based on the Kagome lattice for high power pulse delivery," Optics Express, vol. 18, no. 26, pp. 26655-26665, Dec. 2010.

[26] M. Debbarma et al., "Anti-resonant fibers: a review," Journal of Optics, vol. 20, no. 3, pp. 033001, Feb. 2018.

[27] "Polymethyl Methacrylate (PMMA) - A Review," Journal of Materials Science and Chemical Engineering, Volume 02, Issue 09, September 2014.

[28] "Properties and Applications of Polymethylmethacrylate (PMMA) in Dentistry: A Review of the Literature," Journal of International Oral Health, Volume 7, Issue 6, June 2015.

[29] "High-Density Polyethylene (HDPE) - A Review of the Material and Its Uses," Journal of Polymer Science and Engineering, Volume 9, Issue 2, April 2019.

[30] "Polyethylene Sheathing Materials for Fiber Optic Cables," Wire Journal International, Volume 53, Issue 10, October 2020.

[31] G. Ren, Y. Wang, and P. Shum, "Anti-resonant fiber design for single-mode operation," Optics Letters, vol. 37, no. 9, pp. 1479-1481, May 2012.

[32] R. Yan, W. Ding, S. He, and M. Yang, "Anti-resonant reflecting guidance in optical fibers," Nature Photonics, vol. 6, pp. 732-736, October 2012.

[33] K. Saitoh et al., "Mode-field diameter and cut-off wavelength measurement in a single-mode photonic bandgap fiber," Optics Express, vol. 11, no. 13, pp. 1517-1522, 2003.

[34] Y. Jung et al., "Characterization of large mode area anti-resonant fibers," Optics Express, vol. 22, no. 8, pp. 9526-9535, 2014.

[35] P. Russell, "Photonic crystal fibers," Science, vol. 299, no. 5605, pp. 358-362, 2003.

[36] S. Mukherjee, A. P. S. Chouhan,” Photonic crystal fibers and its applications in gas sensing-a review”, Journal of Physics Conference Series 1531(1):012038, May 2020

[37] A. Agrawal, S. A. Dar, A. Singh, and P. C. Deshmukh, "Terahertz waveguides: a review," Journal of Nanophotonics, vol. 13, no. 1, pp. 1-27, 2019.

[38] V. Setti, L. Vincetti, and A. Argyros, ‘‘Flexible tube lattice fibers for terahertz applications,’’ Opt. Express, vol. 21, no. 3, pp. 3388–3399, 2013

[39] H.Bao,K.Nielsen,O.Bang,andP.U.Jepsen,‘‘Dielectrictubewaveguides with absorptive cladding for broadband, low-dispersion and low loss THz guiding,’’ Sci. Rep., vol. 5, no. 1, Jul. 2015, Art. no. 7620.

[40] M. N. Petrovich, et al., "Recent advances in hollow-core anti-resonant fibers" bOptics Express, vol. 24, no. 13, pp. 14731-14745, 2016.

[41] M. Gebhardt, et al., "Fabrication and Characterization of Anti-Resonant Fibers for High-Power Laser Applications" , Applied Sciences, vol. 10, no. 9, pp. 3066, 2020.

[42] Olszewski, J., et al. "ARROW and anti-resonant hollow-core waveguides in cyclo-olefin polymer." Optical Materials Express 3.8 (2013): 1083-1096.

[43] D. Marcuse, “Calculation of the V parameter for single-mode fibers.” Journal of Lightwave Technology, 3(6), 1082-1085.(1985).

[44] https://www.azom.com/article.aspx?ArticleID=788 (accessed April,2023).

[45] https://www.azom.com/article.aspx?ArticleID=423 (accessed April,2023).

[46] http://textilelearner.blogspot.com/2013/04/teflon-ptfe polytetrafluoroethylene.html (accessed April,2023).

[47] https://geologyscience.com/minerals/topaz/ (accessed April,2023).

[48] H. Liu, H. Wang, Y. Zhang, C. Chen , “High-sensitive measurements of refractive-index and magnetic-field based on liquid-infiltrated photonic crystal fiber with an elliptically-shaped core.”, Optical and Quantum Electronics 52(12), December 2020.

[49] J. Sultana, M. S. Islam et al, ‘’Exploring Low Loss and Single Mode in Antiresonant Tube Lattice Terahertz Fibers.’’IEEE Access, June,2020.