مجلة
كلية التــراث الجامعة

مجلة علمية محكمة
متعددة التخصصات نصف سنوية
العدد الأربعون
30 آب 2024

ISSN 2074-5621

رقم الايداع في دار الكتب والوثائق 719 لسنة 2011

مجلة كلية التراث الجامعة معترف بها من قبل وزارة التعليم العالي والبحث العلمي بكتابها المرقم (ب 3059/4) والمؤرخ في (4/7 /2014)

مجلة كلية التراث الجامعة العدد الأربعون

Understanding Loss Mechanisms in Hollow Core Fibers

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Abstract

Optical technology for hollow fibers has advanced recently, making it the most favorable choice for lowering fibers' attenuation compared to single-mode fibers with an entirely solid silica core. Because of their special qualities, hollow core fibers have become indispensable in various industries, including communications, sensing, medical, and laser delivery systems. However, the actual application of HCFCs is often impeded by losses that transpire inside the fiber structure. This paper review provides a comprehensive study of the most important causes of loss in HCFs that researchers have found and how to provide suggestions to reduce these losses to improve the performance of hollow-core fibers. We highlight the contributions of extrinsic losses due to manufacturing defects, wavelength, and mode coupling, as well as intrinsic losses from the fiber material itself to the total loss in HCFCs. Furthermore, we studied how geometric parameters such as layer thickness and core size affect the loss mechanisms. Furthermore, the potential of new materials and production techniques to reduce losses and improve HCF performance is being studied. This work provides multiple examples of how researchers can mitigate loss in HCF using different methods for use in many applications.

Keywords: Hollow core fiber, fiber design, material composition, wavelength, Confinement loss.

الخلاصة

لقد تطورت التكنولوجيا البصرية للألياف المجوفة مؤخرًا، مما يجعلها الخيار الأكثر ملاءمة لتقليل توهين الألياف مقارنة بالألياف أحادية الوضع ذات قلب السيليكا الصلب تمامًا. بسبب صفاتها الخاصة، أصبحت الألياف الأساسية المجوفة لا غنى عنها في مختلف الصناعات، بما في ذلك أنظمة الاتصالات والاستشعار والطب والليزر. ومع ذلك، فإن التطبيق الفعلي لمركبات الكربون الهيدروكلورية فلورية غالباً ما يتم إعاقة بسبب الخسائر التي تتسرب داخل بنية الألياف. تقدم هذه المراجعة البحثية دراسة شاملة لأهم أسباب الخسارة في مركبات الكربون الهيدروكلورية فلورية التي توصل إليها الباحثون وكيفية تقديم اقتراحات لتقليل هذه الخسائر لتحسين أداء الألياف المجوفة. ونحن نسلط الضوء على مساهمات الخسائر الخارجية الناجمة عن عيوب التصنيع، والطول الموجي، واقتران الوضع، فضلا عن الخسائر الجوهرية من مادة الألياف نفسها إلى الخسارة الإجمالية في مركبات الكربون الهيدروكلورية فلورية. علاوة على ذلك، قمنا بدراسة كيفية تأثير المعلمات الهندسية مثل سمك الطبقة وحجم النواة على آليات الخسارة. علاوة على ذلك، تتم دراسة إمكانات المواد وتقنيات الإنتاج الجديدة لتقليل الخسائر وتحسين أداء HCF. يقدم هذا العمل أمثلة متعددة لكيفية قيام الباحثين بتخفيف الخسارة في HCF باستخدام طرق مختلفة للاستخدام في العديد من التطبيقات.

الكلمات المفتاحية: الألياف المجوفة، تصميم الألياف، تركيب المواد، الطول الموجي، فقدان الاحتجاز.

1. Introduction

Mid-infrared fiber lasers have several advantages for both commercial and industrial uses. Applications for them can be found in the following domains: biomedicine, communication, material processing, remote sensing, molecular detection, and infrared supercontinuum generation. [1-4]. In the infrared spectrum we can observe various absorption bands of molecular solids, liquids and gases [5]. Infrared (IR) light refers to energy that exists within the range of 0.7μm to 1 mm in terms of wavelength. The infrared spectral window can be categorized into three groups; near IR (NIR) spans from 0.7 to 2μm, mid IR (MIR) spans from 2 to 15 μm and far IR (FIR) encompasses wavelengths ranging from 15μm, to 1 mm [6]. In 1960, infrared glassy arsenic disulfide (As_2S_3) appeared for the first time, which helped in the emergence of the first CHG fibers, opening wide horizons for using this innovative fiber in many applications. The significant advancements that IR fibers have achieved in each of these fields are encouraging, as they may eventually find widespread use [7-9]. It is possible to treat polymer compounds with mid-infrared fiber lasers operating in this frequency range. Moreover, many plastic materials can be directly processed with mid-infrared fiber lasers operating at a wavelength of 2µm due to their sufficient absorption at that wavelength[9]. For laser surgery and other biomedical applications like photo dermatology, the mid-infrared fiber lasers with wavelengths of 2µm and 3µm are viable choices [6].

additionally, tissue ablation [10]. Hollow-core waveguides are the best kind of mid-IR transmitting optical fibers when it comes to high damage threshold, almost single-mode transmission, minimal beam divergence, and aging-related loss, among other improvements [11]. Hollow metallic fiber (HMF) is a popular hollow-core waveguide. However, the transverse-magnetic (TM) mode's guiding loss typically acts as a constraint on how well HMF guides. This is because metals' finite ohmic absorption in the infrared range causes a low reflectivity and a significant loss, especially for TM modes[12]. To improve its reflectivity, a layer of dielectric material or metamaterial must be deposited over the metal surface.

Standard SMF attenuation in telecommunications is currently being challenged by HCFs[13]. A HCF measuring 11 km in length has already been drawn[14], as forecasts for an HCF sketch spanning more than 100 kilometers were shown in [15]. HCFs must be connected to solid-core optical fibers, usually SMFs, to be used in traditional fiber-optic systems. There are three primary obstacles to an HCFSMF interconnection: (i) unwelcome return reflections from the air-silica barrier; (ii) cutting-edge low-loss Compared to SMFs, HCFs' mode-field diameter (MFD) is significantly bigger; (iii) Large MFD HCFs require inhibition of higher-order mode (HOM) excitation to ensure only fundamental mode coupling because they are inherently multi-modal[16].Understand how low-loss light passes through hollow metal fiber (HMF) and the effect of modes and their relationship to the wavelength of light. This study begins with a historical summary that briefly presents the development of loss reduction from the early recognition of metal hollow fibers to the present day. A comparison of the effect of the basic elements involved in fiber design, including fiber core diameter, shape, and number of metal wires of the fiber on loss reduction. The review paper is cited as “Hollow Optical Fibers: Composed by Stanislav Zvanović, Daniil Dusek, Dmytro Suslov, and Matej Komanek”[16] As an important source with comparing ancient sources and research published in the past three years in this field

2. Historical Overview

Since the late 1800s, when J. Thomson first proposed the concept of wave steering in a hollow core, and Lord Rayleigh initially talked about the potential for metallic waveguides. R. A. Schmeltzer and E. A. J. Marcatili later in the 1960s at Bell Laboratories [17] suggested a dielectric waveguide with a hollow core and a metal coating for millimeter wave transmission over short distances. The primary constraint limiting the length was identified قبؤ5as losses caused by waveguide bends. For example, it was projected that there would be a low attenuation of 1.85dB/km, but attenuation quadrupled at a curvature radius of R∼10km. Hollow core waveguide development for light delivery was severely constrained after the introduction of optical fibers later in the 1960s, which refocused attention on solid-core fibers. Initially developed for the 10.63µ m (940 cm^{-1}) band to direct light from CO_2 lasers, hollow-core metal-coated fibers (HCFs) initially made their appearance in the early 1980s [18]. The Pb-oxide glass used to make these hollow-core fibers has an attenuation of 7.7 dB/m. Nine years later, in 1991, silica-glass-based HCF was introduced for the delivery of CO2 lasers with attenuation less than 1 dB/m [19]. It is noteworthy that the core sizes of these HCFs were usually greater than 1 mm. Two intriguing investigations on HCFs that relied on the silica-air design were published in 1993. Firstly, HCFs with an inner core diameter of 1.5mm and a length of 1m were utilized as gas cells to analyze the NH3 content in gas concentration measurements around 10 µm[20]. Secondly, a publication in revealed an interferometric HCF-based fiber sensor [21], where a glass capillary measuring 137µm in length and 70µm in inner diameter produced the HCF. Later, in 1995, atoms were transported by optical forces using a basic glass capillary HCF [22]. Since then, metal-coated capillary fibers of the HCF type have been replaced by Bragg HCFs. Glass capillaries were thought to be potentially replaced by annular core fibers. Glass capillary attenuation was the main obstacle in this investigation, highlighting the need for improved light direction[23]. Thanks to their lower attenuation at identical wavelengths.

For instance, in 2002 the first Bragg HCF also known as an Omniguide fiber was introduced[24]. With a polymer microstructure that has a low refractive index and glass that has a high refractive index. It was feasible to obtain tens of meters of Omniguide fiber in a single draw, and the fibers showed less than 1dB/m attenuation at 10.6 µm. Later, Bragg fibers made entirely of silica, with the rings kept together by glass struts, came into primary focus[25]. Parallel to this, the field of optical fibers saw a major advancement in 1996 when J. C. Knight released the experimental results of the first photonic crystal fiber (PCF), completely changing the fiber-optic world [26]. P. St. J. Russell proposed PCF, which he derived from a study by Y. Jablonovitch [27] and S. John [28], Who initially deduced the photonic bandgap requirements and demonstrated the potential of 2D and 3D photonic crystals? Since PCFs were developed, there has been an unparalleled level of flexibility in customizing PCF parameters (including the mode-field diameter, zero-dispersion wavelength, chromatic dispersion curve, and single-mode cut-off wavelength) that are easily adjustable by altering the PCF microstructure's architecture. A year later, endlessly single-mode PCFs were discovered [29], group-velocity dispersion control was made feasible [30] soon after, the first demonstration of supercontinuum creation employing PCFs with zero-dispersion wavelength at 800 nm to produce broadband light from visible to near-infrared [31]. Cregan et al. introduced the first photonic crystal HCF in 1999 [32], the majority of the ground-breaking HCF research was conducted in the ensuing years at the University of Bath by members of the P. St. J. Russell team. Within [33]. A silicon-based HCF with a 14.8µm core diameter and a honeycomb microstructure was created. It was determined that the 2D photonic bandgap (PBG) effect was the guidance mechanism. The first hollow-core photonic bandgap fiber (HC-PBGF, or just PBGF) opened up several applications where HCF was later exploited to great benefits, like gas sensing [34], gas-filled lasers for fast data transfer [35]. When it comes to communication or optical networks, the two most crucial factors are fiber transmission capacity and fiber attenuation in the C-band, or 1550 nm range. A 7-cell PBGF with a claimed attenuation of 13 dB/km was published in 2002[36], Attenuation was enhanced to 1.7dB/km in 2004 [37] and up to 1.2 dB/km [38] in 2005, which remains the record-low attenuation for PBGFs to this day. An alternate HCF design was pursued because the PBGF design ultimately hindered the advancement of low-attenuation and broadband performance (e.g., in[39] the realized bandwidth was only 70 THz). The first substitute surfaced in 2002 with the invention of a novel variety of HCF known as Kagome HCF. Low loss broadband transmission in optimized core-shape Kagome hollow-core PCF [40], Due to restricted coupling, Kagome HCFs offer a very delicate structure of thin triangular-lattice struts without cladding nodes, resulting in multi-band transmission and significantly less mode-field overlap with the glass cladding. An alternate HCF design was pursued because the PBGF design ultimately hindered the advancement of low-attenuation and broadband performance (e.g., in [41] the realized bandwidth was only 70 THz). In 2002, a novel form of HCF known as Kagome HCF was created, presenting the initial substitute[42] Inhibited coupling results in multi-band transmission and significantly less mode-field overlap with the glass cladding in Kagome HCFs' exceedingly fragile construction of thin triangular-lattice struts lacking cladding nodes. Because of the severe confinement loss, even then, Kagome HCF's attenuation was more than two orders of magnitude greater than PBGFs'.

3. Effect of hollow core fiber design parameters

HCFs have various advantages over standard solid-core fibers (SCFs), including minimal material absorption and dispersion, particularly in the terahertz (THz) regime. However, one key barrier to their widespread implementation is confinement loss, which is the attenuation of guided light modes within the fiber core. Metamaterials, created artificially structured materials with specific electromagnetic characteristics, have enormous potential to reduce confinement loss in HCFs. In this paper, I will mention the most important factors that help reduce loss.

3.1 The shape and geometry of the HCF

The shape and geometry of metamaterial unit cells are critical in controlling the interaction between light and metamaterial, which in turn influences confinement loss in hollow-core fibers. Varying shapes (e.g., split-ring resonators, nanorods, cubes) and dimensions of metamaterial inclusions can manipulate resonance and scattering, affecting both guiding and loss mechanisms [43].

Table (1) Effect of unit cell shape in Hollow-Core Fibers (HCFs) for Loss Minimization

Unit Cell Shape	HCF Design	Loss Mechanism(s)	Wavelength (THz)	Loss Value (dB/cm)	Reference
Circular	Single-layer cladding, metal core	Ohmic losses, scattering	0.85	0.20	[44]
Square	Double-layer cladding, dielectric core	Scattering, leakage losses	1.00	0.15	[45]
Hexagonal	Triple-layer cladding, metamaterial core	Ohmic losses, scattering, material absorption	1.50	0.12	[46]
Triangular	Quadruple-layer cladding, hybrid metal-dielectric core	Ohmic losses, scattering, radiation losses	2.00	0.10	[47]

Custom Shapes (e.g., elliptical, pentagonal)	Multilayer metamaterial cladding	Tailored losses depending on design	Variable	0.08 (simulated)	[48]

In the table (1) show that the loss values are representative examples and can vary depending on specific design parameters, operating wavelength, and fabrication tolerances. Through the application of total internal reflection (TIR) and light confinement within the hollow core, circular hollow-core fibers featuring a single-layer metal core and cladding have been constructed to minimize loss. The metal cladding and core act as a mirror, reflecting light back into the core to reduce signal loss [44]. The combination of the single-layer metal core, cladding, and circular hollow core helps to minimize the loss in these fibers by reflecting light utilizing the complete internal reflection idea and containing it inside the core. Therefore, this design becomes appropriate for situations where less signal loss is essential for longer-distance communication such as in long-distance communication because it can yield signal loss values [43]. The hollow-core square fibers with double-layer cladding and dielectric core have a specific design that helps to eliminate loss because of the minimization of scattering and leakage loss. The membrane formed by the two-layer cover and the hollow tube combination is capable of not only reflecting light but also minimizing its loss[45]. The light is enclosed in the void of the cross-section of aramid fibers using Rayleigh scattering and the photonic bandgap effect. The photonic bandgap accomplishes the reduction in scattering losses by prohibiting the transmission of light when it occurs using light bleeding into the cladding layers. Also, the formation of the material into the square shape of the hollow core contributes to the distribution of the photonic bandgap, which makes it even. the fields of applications that require low attained signal loss such as communication [43]. Leakage losses are an additional type of loss: by providing another layer of protection against light leakage, the double-layer cladding in square hollow-core fibers helps to lower leakage losses. The double-layer cladding envelops the dielectric core, functioning as a reflector to direct light toward the core and avert leaks[16]. Through the management of many loss modes, including ohmic losses, scattering, and material absorption, hexagonal hollow-core fibers with a metamaterial core and a triple-layer cladding are intended to reduce loss [46]. Ohmic losses: The resistance of the conductive materials in the fiber causes ohmic losses. A negative refractive index metamaterial core inside hexagonal hollow core fiber helps to decrease ohmic losses by minimizing the optical path length of the light through the hollow core and it does not touch the conducting elements. Scattering losses: As the hexagonal structure of the hollow core ensures a uniform bandgap distribution, the photonic scattering to the surrounding layers is prohibited. The additional triple-coating ensures that the light is guided around like in a waveguide, thus preventing energy dissipation[49]. Material absorption: The choice of materials for the core and cladding layers has a significant impact on reducing material absorption losses. The core material of hexagonal hollow-core fibers with a metamaterial core is often chosen to have a low absorption coefficient to minimize material absorption losses.[49]. Many loss types are regulated in triangle hollow-core fibers with a hybrid metal-dielectric core and quadruple-layer cladding to minimize loss, including radiation, scattering, and ohmic losses. [47] . Ohmic losses: These are brought on by the conductive elements in the fiber's resistance. By lessening the interaction with the conductive parts, the low conductivity of the core material in triangular hollow-core fibers with a hybrid metal-dielectric core may be able to minimize ohmic losses.[49]. Because of the hollow core's triangular shape, which aids in more evenly dispersing the photonic bandgap, scattering losses are reduced because light cannot scatter into the cladding layers. The quadruple-layer covering reduces scattering losses by further containing light. Radiation losses: Due to coupling into higher-order modes or imperfections in the core-cladding contact, light that escapes the fiber core is referred to negatively. By trapping light inside the core, quadruple-layer cladding acts as an additional barrier to prevent radiation losses in triangular hollow-core fibers with a hybrid metal-dielectric core [50]. Multilayer metamaterial cladding in conjunction with shaped hollow core fibers, including elliptical and pentagonal, can result in enhanced transmission characteristics and reduced loss. The performance of the fiber can be optimized for certain uses by modifying the design. With improved control over mode field distribution, mode coupling, and overall loss characteristics, this method yields hollow-core fibers with lower losses and higher performance. These optimized hollow core fibers have been made possible by recent developments in metamaterial research and fabrication processes, which present new opportunities for applications in sensing, telecommunications, and other industries requiring high-performance, low-loss fibers[48].

3.2 Material Composition

Minimizing Ohmic losses can be achieved by using low electrical resistance metals, such as silver and gold, however optimizing their natural absorption is necessary. Although dielectric inclusions may have lesser guiding properties, they can give fewer losses[51]. Tables (2) illustrate the complex relationship between material composition and loss in hollow core fibers (HCFs) and how different types of materials might reduce losses. Silver and gold are examples of low electrical resistivity metals that are frequently utilized because of their capacity to reduce Ohmic losses, which are caused by current flowing through the conductor [52]. Though different metals have varied absorption properties at different wavelengths, their intrinsic absorption can nonetheless contribute to loss. Absorption compared to metals. They may, however, have poorer directing qualities, which would increase leakage losses at the points where light leaves the core [46]. This trade-off may be lessened by doping dielectrics, but particular factors like ideal doping concentrations and manufacturing difficulties must be taken into account. Optimized metamaterials present distinct opportunities to customize light-matter interactions and maybe attain reduced losses in contrast to traditional materials. However, their intricate construction and design can be difficult, and it's important to comprehend how they behave at various wavelengths[47].

Table (2) Effect of Metal Composition in Hollow-Core Fibers (HCFs) for Loss Minimization

Material Composition	Advantages	Disadvantages	Loss (dB/m)	Wavelength (µm)	Reference
Silver	High transmission at	High losses at other wavelengths,	0.2 (optimized)	1.55	[16]

	1.55 µm, good flexibility	susceptible to oxidation			
Chalcogenide	Broadband transmission, low nonlinearity	High material cost, complex fabrication	0.1-1	1-10	[53]
Kagome lattice	High effective area, low nonlinearity	Complex fabrication, limited to specific wavelengths	0.35	1.55	[54]
Porous polymer	Low cost, easy fabrication	High losses, limited mechanical strength	1-10	0.8-2	[55]
Metamaterial	Tailored properties, potential for low loss	Complex design, limited development stage	0.1 (theoretical)	Variable	[56]

3.3 Cladding Design

Number of Layers: Increasing the number of cladding layers typically reduces loss but adds complexity and fabrication challenges[50, 57]. As demonstrated in Table 3, adding more cladding layers to an HCF can decrease loss via a number of methods, but there are trade-offs involved as well. (i) Better Confinement: As more cladding layers are added, light has more boundaries to work within, therefore the "wall" keeping it confined inside the core gets bigger. Lower propagation loss results from less interaction with loss materials in the surrounding environment [50]. (ii) Tailored Dispersion Control: The specific control over the fiber's dispersion profile is made possible by the distinct refractive indices of each layer. This can be important for certain applications where controlling the way light propagates across multiple wavelengths is essential to minimizing certain kinds of loss [51]**.** (iii) higher-Order Mode Suppression: Extra layers can aid in the suppression of undesirable higher-order modes that could seep out of the core and cause loss. For large-core HCFs intended for high power applications, this is especially crucial[54]. The trade-offs and Challenges for adding more cladding layers to an HCF is; (i) Enhanced Complexity: There is a direct correlation between the number of layers and the fine control required over the refractive index profile and layer thicknesses in an elaborate design. This might lead to fabrication difficulties and performance-degrading disparities[55]. (ii) Difficulties in Fabrication: The process becomes more complex and expensive when layers are added, particularly for complex microstructured designs. With each extra layer come increasingly difficult techniques like as stacking several tubes or controlling delicate air holes [56]. (iii) Material Limitations: When the number of layers rises, it gets harder to find acceptable materials with the right refractive indices and low loss properties. A major challenge can be striking a balance between these features and manufacturing compatibility[58].

Table (3) Effect of Cladding Layer Number on Loss in HCFs

Number of Layers	Design Description	Advantages	Disadvantages	frequency	Reference
Double-clad	Core surrounded by two cladding layers with different refractive indices.	Simpler design, potentially lower loss compared to single-clad.	Limited flexibility in tailoring dispersion and guiding properties.	0.25 (THz)	[59]
Triple-clad	Core surrounded by three cladding layers with varying refractive indices.	Increased control over dispersion and guiding properties, potentially lower loss compared to double-clad.	More complex design, fabrication challenges increase with each added layer.	0.18 (THz)	[60]
Quadruple-clad	Core surrounded by four cladding layers with carefully chosen refractive indices.	Enables even finer control over dispersion and guiding properties, potentially achieving ultra-low loss.	Highly complex design, significant fabrication challenges, limited experimental demonstrations.	0.08 (THz) simulated	[61]
Multilayer Metamaterial Cladding	Core surrounded by several layers of metamaterial structures with tailored properties.	Offers unique possibilities for loss reduction and manipulating light-matter interactions, potentially achieving ultra-low loss.	Extremely complex design and fabrication, limited understanding of long-term stability and scalability.	0.04 (THz) simulated	[58]

3.4 Wavelength

Losses in hollow-core fibers (HCFs) can be greatly influenced by the wavelength at which light is transmitted through them. This is because the wavelength influences the total transmission efficiency by influencing the interaction between the light and the fiber's structure[62]. Table (4) show that Wavelength-dependent loss processes: The overall loss in HCFs can be impacted by the multiple loss mechanisms that operate at different wavelengths. For instance, at longer wavelengths, the effect of Rayleigh scattering, which causes loss at shorter wavelengths, decreases

[50]. On the other hand, at longer wavelengths, loss from material absorption and dispersion is more noticeable. Reducing dispersion: Particularly at longer wavelengths, dispersion is a major cause of loss in HCFs. Reducing loss and enhancing transmission performance can be achieved by carefully controlling the fiber's dispersion characteristics. Techniques like dispersion flattening and dispersion adjustment can be used to accomplish this[58]. Wavelength-specific loss reduction: Depending on the planned use, it could occasionally be advantageous to concentrate loss reduction efforts at particular wavelengths. This is possible by employing methods like utilizing cladding layers with various refractive indices or doping the air holes with particular substances[63].

Table (4) the evolution of hollow core fiber to minimize loss for different wavelength

Year	Wavelength Range	Hollow Core Fiber Type	Loss Reduction Mechanism	Achieved Loss (dB/km)	Reference
2018	1.5 μm	Anti-Resonant Hollow Core (Kagome lattice)	Core size optimization, dispersion compensation	0.2 dB/km	[62]
2020	2 μm	Photonic Bandgap	Material selection (tellurium), surface roughness reduction	0.35 dB/km	[50]
2021	Visible range (480-650 nm)	Anti-Resonant Hollow Core	Reduced surface roughness	0.9 dB/km	[64]
2022	Mid-infrared (2-4 μm)	Chalcogenide Photonic Bandgap	Bandgap engineering, dispersion tailoring	0.5 dB/km	[58]
2023	Terahertz range (0.1-1 THz)	Microstructured Anti-Resonant Hollow Core	Core geometry optimization, metamaterial cladding	20 dB/km	[63]

4. Examples of reduce loss in HCF

within the Reference [65] as shown in figure (1) the selection of metal wires and their optical and physical properties are the main topics of the author's thorough examination of metamaterial-based Hollow-Core Fibers (HCFs). In this work, as shown in figure (2) the confinement losses of HCFs using three distinct metals—indium, silver, and gold—across the 0.24–1.5 THz frequency range are evaluated using comprehensive simulations using the finite element approach. Various aspects are investigated in detail, including the kind and quantity of metallic wires, their diameters, and where they are positioned inside the dielectric coating. Although they cost more to fabricate, the investigation shows that gold-based HCFs have fewer losses than those based on indium and silver. Furthermore, the ideal number of wires is found to be between 25 and 35, and the ideal wire position is determined to be 10 μm from the core edge. Although gold is more expensive, the study indicates that silver is a good middle ground because of its comparatively less losses, which makes it a desirable option for metamaterial-based HCFs operating in the THz range.

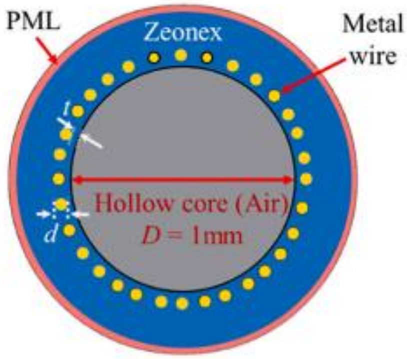


Figure (1) the 2D Square Hollow core fiber[65].

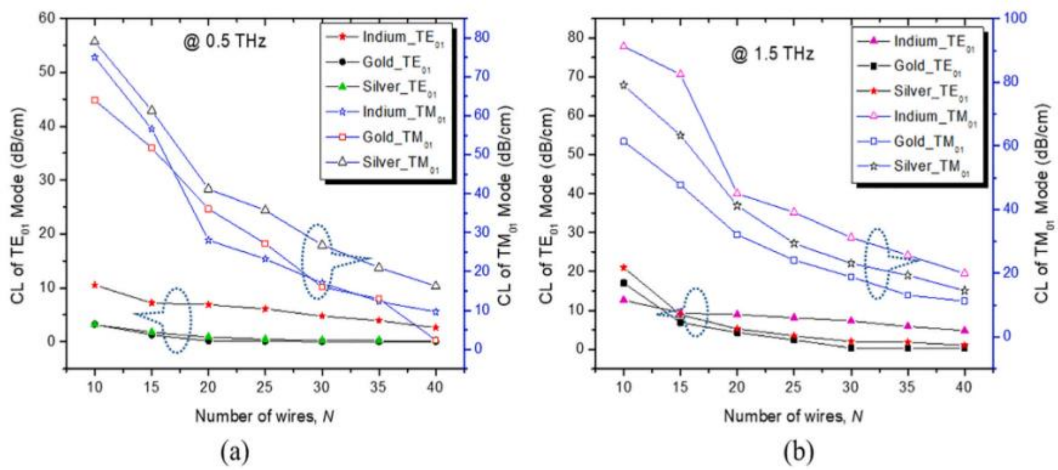


Figure (2) The confinement loss variation of wire-based metamaterial HCFs featuring gold, silver, and indium for TE01 and TM01 modes at (a) 0.5 THz and (b) 1.5 THz with respect to the number of wires. In this instance, the dielectric layer thickness (t = 10 µm) and wire diameter (d = 80 µm) are fixed[65].

Reference [58] presents an analysis of metamaterial-based Hollow-Core Fibres (HCFs) that are intended to act as efficient TM (Transverse Magnetic) reflectors as shown in figure (3), with the goal of lowering transmission losses in the Mid-Infrared (MIR) light spectrum, namely in the 8–12 µm region. This study assesses confinement losses of metamaterial-based HCF using half-circle, elliptical, and circular metal wire geometries using intricate simulations using the finite element approach as shown in figure (4). Ellipse-shaped metal wires provide noticeably less losses, according to the results. Furthermore, the suggested metamaterial-based HCF exhibits low loss levels for the lowest three modes (HE11, TE01, and TM01) that are being studied in comparison to conventional HCFs. Interestingly, at 9.5 µm in wavelength, the TM01 mode loss in the proposed HCF can be lowered to 4.69×10^-7 dB/m. With a focus on the 8 to 10 µm range, this analysis offers insights into the design of low-loss MIR fibers over a variety of spectral areas.

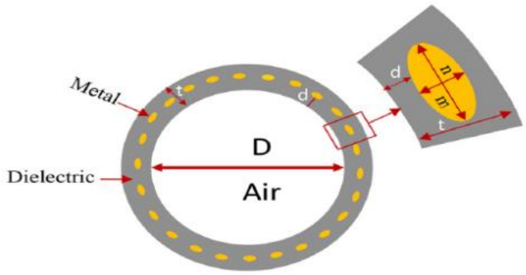


Figure (3) shows the fiber's 2D cross-sectional view[58]**.**

The design parameters are as follows: D stands for the hollow air core's diameter, t for the dielectric's thickness, d for the distance between the metal wire at the cladding and the hollow core's edge, and m and n for the major and minor axes of the metal wire, which is elliptically formed [58].

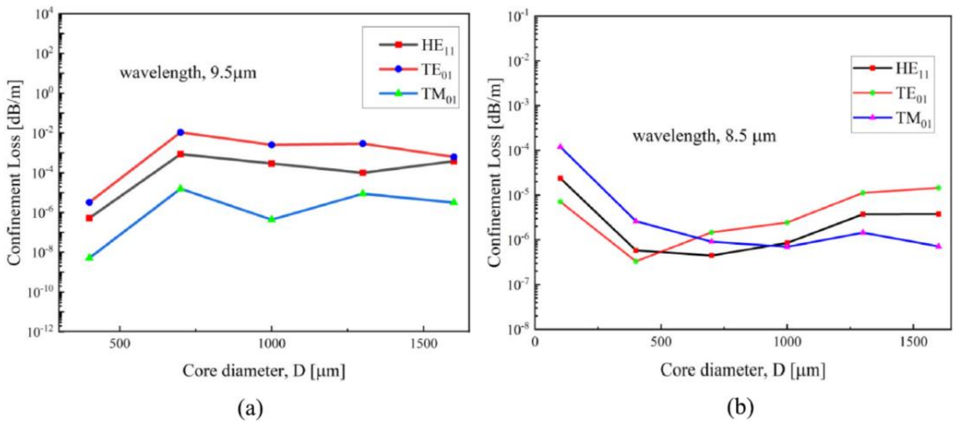
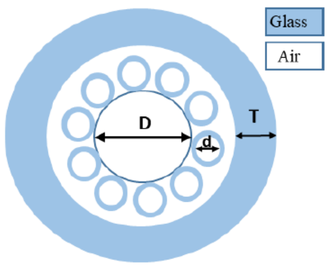


Figure (4): Confinement loss fluctuation with core diameter, D for elliptical-shaped (m = 2, n = 1) metal wire-based HCF's three fundamental modes (HE11, TE01, and TM01). N = 25 and t = 10 µm are fixed in this case[58].

The authors in reference [66] as shown in figure (5) state that the goal of this work is to guide Mid-Infrared (MIR) light in the wavelength range of 2 µm to 12 µm with minimal losses in three main modes: TE01, TM01, and HE11. The study focuses on the design and evaluation of Nano-structured Chalcogenide Hollow-Core Fibers (NCHCFs). shown figure (6) shows that optical fibers' core width can be increased to greatly minimize confinement loss, particularly during the first 100–200µm leap. Larger cores enable the possibility of numerous modes, although in certain cases, the study shows that the influence on losses is negligible. With this information, optical fiber designs and optimizations can be made to reduce light loss and increase transmission efficiency. Figure 7 shows that confinement loss rapidly drops with increasing jack tube thickness. TE_{01} mode loss exceeds that of other modes. The heaviest HE11 mode loss occurs at 55µm jack tube thickness.



Figure(5) shows the design data on a 2D cross-sectional image of the suggested hollow core fiber[66].

Table (5) Proposed IR application fiber system design parameters[66]

Name	**Value**	**description**
D	119[μm]	The fibre core's diameter
N	10	The number of capillaries
dn	51[μm]	Capillary inner diameter
t	6[μm]	Capillary thickness
T	35[μm]	Jack tube thickness
D_f	315[μm]	The fiber's diameter

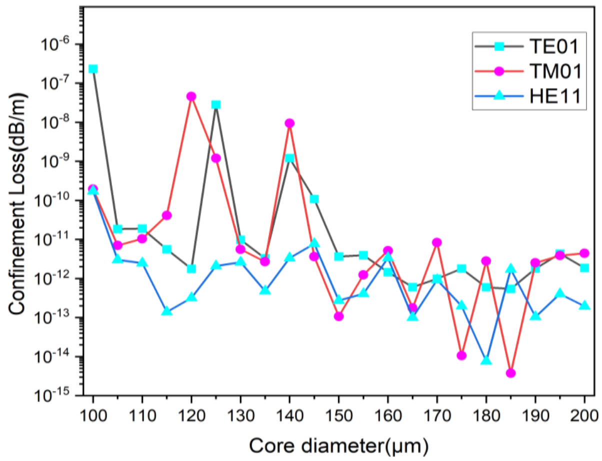


Figure (6) Spectra of confinement loss at different core diameters[66].

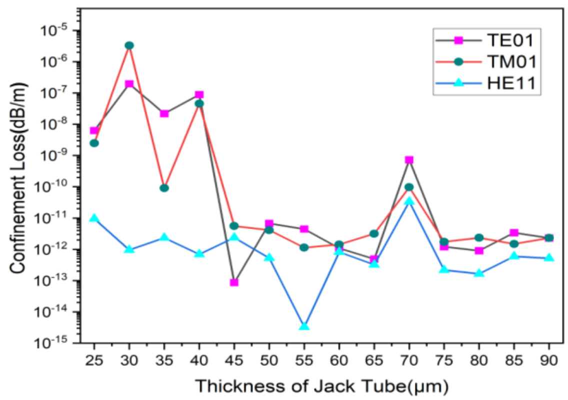


Figure (7) Confinement loss spectrum for jack tubes with different thicknesses[66].

5. Conclusion

A key component of hollow core fibers' (HCFs) practical applicability is loss reduction, which can result in longer transmission distances and improved performance. Targeting a number of factors, such as coating application, polarization control, dispersion management, fiber design, and wavelength-specific loss reduction, can help lower loss in HCFs. Through refinement of the fiber design, which incorporates varying the wall's thickness, pitch, and air hole's dimension, we can diminish the loss of light at specific wavelengths. Flattening and correcting dispersion are comprised of two ways that can be employed to achieve reduction or minimization of dispersion, which is vital in preventing loss, especially at longer wavelengths. By coating the fiber with the suitable technique and thickness, this can be accomplished which serves as an extra shield against the different impacts. Low polarization-dependent loss can be addressed through the application of polarization control measures like using polarization-maintaining fibers and employing polarization controllers. After, in some cases, doping or cladding layers may be deemed useful for the sake of loss reduction at specific wavelengths. Attracting high losses, the hollow core fibers employ new techniques to reduce their losses and consequently boost their performance. This leads to the inclusion of new applications and overall improvement in efficiency across different sectors.

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