

Research Progress of Hollow-Core Anti-Resonant Fibers for High-Capacity Optical Communications

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ABSTRACT

New technologies connecting artificial intelligence, big model training, cloud computing and data center are constantly developing. The traditional single-mode fiber (solid-core single-mode fiber) is close to the limit in terms of signal transmission loss, adverse effects and transmission time, and it is not enough for the next generation of ultra-large data transmission optical communication systems. Hollow-core anti-resonant fiber (HC-ARF) is a kind of non-density optical fiber, mainly the optical fiber through which light passes in the air by anti-resonant. If it can be used for high-performance lighting transmission in the future, it will attract many people's attention. This study summarizes the recent progress of HC-ARF in optical communication for transmitting a large amount of data, and illustrates the future development prospects. Including historical development, the structure of light advance, the evolution of technology, the method of improving structural parameters and the kung fu of dispersion-loss and other important designed combat modes. This paper summarizes the latest progress of ultra-long distance low loss transmission, low delay communication and space division multiplexing system, and discusses the main topics in precision manufacturing, system compatibility and practical application. Finally, HC-ARF shows great potential to improve the transmission efficiency and system capacity in optical communication, but to achieve large-scale practical use, structural reliability, manufacturing technology and system integration need to be further improved, providing important insights for the next generation of high-speed and large-capacity optical communication systems.

Keywords: Hollow-Core Anti-Resonant Fiber; High-Capacity Optical Communications; Ultra-Low Loss; Low Nonlinearity; Low-Latency Transmission; Space-Division Multiplexing

1. INTRODUCTION

With the continuous development of new technologies such as large AI models, cloud computing, data center interconnect (DCI) and 6G communications, network traffic and computing power all over the world are constantly developing. Moreover, optical communication systems are developing to carry more data faster and with less waiting time. As an important foundation of modern information network, fiber-optic communication undertakes most of the tasks of data transmission in the world. However, due to the increasing amount of transmission, the previous solid-core single-mode fibers gradually approached the physical limit, and hit a wall due to transmission loss, optical nonlinearity and transmission delay. Therefore, it is difficult to continue to meet the development needs of the next generation of ultra-high speed and large capacity optical communications [1-3].

Hollow-core anti-resonant fibers (HC-ARF) is a material obtained by using an anti-resonant guiding mechanism to confine most of the light in the air core, significantly reducing material loss and nonlinear effects. In addition, it has the advantages of low latency, spacious transmission windows, and structural design that can be made freely. HC-ARF is considered as an important technical way to exceed the performance limit of traditional solid-core fibers and support a new generation of large-capacity optical communications. In recent years, due to the continuous progress of anti-resonant structure design, precision manufacturing method and system integration technology, HC-ARF has appeared ultra-low loss, low-loss, large capacity transmission and space-division multiplexing. However, there are still many problems in precision manufacturing, low-loss connection, system compatibility and mass production, which hinder their wider application [4-8].

This paper describes the research progress of hollow-core anti-resonant fibers for high-capacity optical communication. The development history of HC-ARFs, the design method of key structures and the methods to improve transmission performance are introduced in an orderly manner, with special attention to the latest research results of ultra-low loss

transmission, low delay transmission and space division multiplexing. Combined with the huge project in engineering application, the future development direction is also considered, aiming at becoming a reference for structural design, engineering application and development of a new generation of high-speed optical networks using hollow-core anti-resonant fibers [9-10].

2. THE LIGHT-GUIDING PRINCIPLE AND STRUCTURAL DESIGN OF HOLLOW-CORE ANTI-RESONANT FIBERS

2.1 Light Guide Principle

Hollow-core anti-resonant fiber (HC-ARF) is a type of new hollow-core fiber that uses anti-resonance to transmit light. Its guiding mechanism is different from traditional solid-core silica fibers, which rely on total internal reflection, and also different from hollow-core photonic bandgap fibers (HC-PBGF), which use photonic bandgap guiding. In HC-ARF, the thin glass walls around the core create anti-resonance conditions, keeping the light mostly confined to the air core over the operating wavelengths, which helps achieve low-loss transmission. As shown in Figure 1.

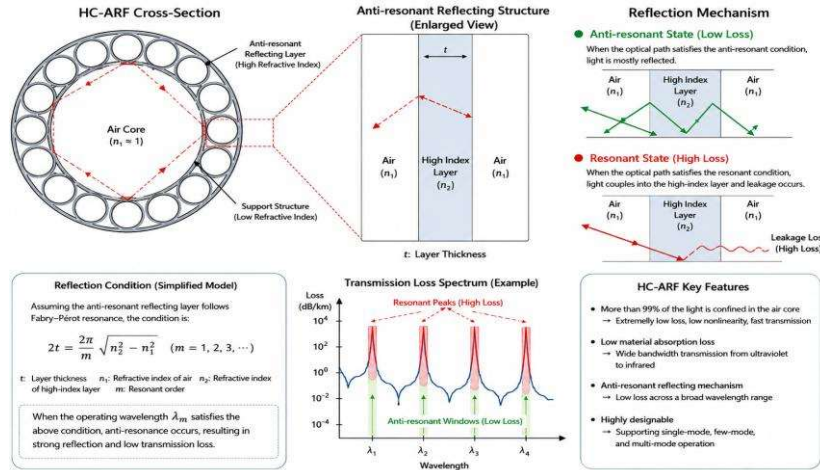


Figure 1. Schematic of HC-ARF anti-resonant light guiding principle.

According to the anti-resonant guiding theory, the cladding thin wall can be seen as a Fabry-Pérot resonant cavity, and its resonant wavelength can be expressed as [11]:

$$\lambda_m = \frac{2t}{m} \sqrt{n_2^2 - n_1^2} \quad (1)$$

In the formula, the cladding glass wall thickness is, and are the refractive indices of air and quartz glass, respectively, while is the resonance order. When the operating wavelength avoids the resonant wavelength, the cladding is in an anti-resonant state, making it difficult for the light field to couple into the glass cladding, which significantly reduces leakage loss. On the other hand, when the operating wavelength is close to the resonant wavelength, light energy easily leaks into the cladding, and transmission loss increases rapidly. Therefore, the anti-resonant wall thickness is a key structural parameter that determines the working wavelength range of HC-ARF, limits loss, and affects single-mode transmission performance.

Since most of the optical power propagates in the air core, HC-ARF significantly reduces the interaction between the light field and quartz material, giving it advantages like ultra-low loss, ultra-low nonlinearity, and low transmission delay, providing new technical options for high-speed, high-capacity, and ultra-long-distance optical communication. In recent years, with the continuous development of anti-resonant guidance theory and fabrication techniques, HC-ARF has gradually become an important research focus in the field of hollow-core fibers, and its structural design has evolved from early simple anti-resonant structures to high-performance structures with multiple nesting, node-free designs, and multiple units [12].

2.2 Typical Structural Evolution

The development of hollow-core anti-resonant fibers (HC-ARF) has always focused on reducing transmission loss, widening operational bandwidth, and improving single-mode transmission performance. With the continuous improvement of anti-resonant guiding theory, HC-ARF has gradually evolved from the early negative curvature structures to newer designs like nested, multi-nested, and nodeless structures, continuously enhancing transmission performance.

Early HC-ARFs mainly used a negative curvature fiber (NCF) design, which introduced negatively curved glass capillaries around the air core to effectively reduce coupling between the core and cladding modes, thus lowering confinement loss. Compared to hollow-core photonic bandgap fibers (HC-PBGF), this structure is easier to manufacture, has a wider operational bandwidth, and is more tolerant in production, though issues like higher leakage loss and insufficient suppression of higher-order modes remain. To further reduce transmission loss, researchers proposed the nested anti-resonant fiber (NANF), which adds nested thin-wall structures inside the capillaries to extend the light leakage path, further reducing confinement loss and improving mode confinement. Building on this, the double nested anti-resonant nodeless fiber (DNANF) uses a double nested design and a nodeless structure to effectively reduce scattering loss and mode coupling, bringing transmission loss closer to the theoretical limit. Currently, DNANF has become a representative structure for achieving ultra-low-loss transmission, pushing HC-ARF toward the 0.05 dB/km range ^[13].

In recent years, structural optimization of HC-ARF has expanded from just reducing loss to enabling broadband transmission, single-polarization transmission, multi-core hollow structures, and high-power laser transmission ^[14-16]. By optimizing anti-resonant wall thickness, air hole size, the number of capillaries, and cladding configuration, the low-loss transmission window can be further broadened, single-mode transmission and polarization-maintaining performance improved, and manufacturing tolerance enhanced, laying the foundation for the development of high-speed, high-capacity optical communication and space-division multiplexing systems.

2.3 Key Structural Optimization Strategies

The performance improvement of hollow-core anti-resonant fibers (HC-ARF) mainly depends on the continuous optimization of structural parameters. The main goal is to achieve broadband transmission, good single-mode characteristics and high manufacturing tolerance while reducing confinement loss. In recent years, researchers have done a lot of research on the thickness of the anti-resonant wall, cladding structure, capillary configuration and multifunctional design, so that HC-ARF has been developing towards ultra-low loss and high performance ^{[11][12]}.

The thickness of the reflecting wall is an important factor affecting the passage of HC-ARF light. According to the theory of anti-resonant guiding, different wall thickness will also change the wavelength range of anti-resonant. Therefore, if the thickness of the wall is well adjusted, the loss of light escaping outward will be reduced, and the range of light passing through will be expanded with less loss. At the same time, the number of capillary, the size of air hole, the size of core and other parameters will also affect the role of limiting light modes and suppressing high-order modes. If the structure is well designed, the interference between modes can be further reduced and the single-mode light transmission performance can be improved.

In addition to the adjustment of geometric parameters, the new cladding structure is also a major research topic in recent years. Nested anti-resonant structure, nodal-free structure and special form of capillary can reduce the scattering loss at the interface between air and glass, strengthen the closure of basic modes, and tolerate errors when making. Among them, the double-nested nodal-free anti-resonant fiber (DNANF) is a representative structure that transmits light with minimal loss, and the transmission loss is less than 0.08 dB/km ^{[13][17]}.

With the increase of application occasions, the structural design of HC-ARF has changed from only reducing loss to improving various purposes at the same time. Balance between broadband transmission, polarization maintenance, multi-core space-division multiplexing and high-power laser transmission ^{[15][16]}. In the future, HC-ARF will further improve its performance and provide an even better transmission medium for optical communication that can send more data quickly through intelligent design optimization, high-precision manufacturing and new microstructure forms.

3. RESEARCH PROGRESS ON THE TRANSMISSION PERFORMANCE OF HOLLOW-CORE ANTI-RESONANT OPTICAL FIBERS

3.1 Ultra-low loss transmission

Ultra-low transmission loss is an important index of hollow-core anti-resonant fibers (HC-ARF) for long-distance optical communication. In recent years, anti-resonant structural design and fabrication are getting better and better, and the transmission loss of HC-ARF continues to decline, reflecting the theoretical limitations of ordinary solid-core silica fibers (about 0.14 dB/km).

Recently, nested anti-resonant fibers (NANF) and double nested anti-resonant nodeless fibers (DNANF) have become the mainstream of ultra-low-loss design. By adjusting the thickness of anti-resonant wall, reducing the scattering loss of air-glass interface and suppressing the leakage of basic modes, the original loss of HC-ARF is close to the theoretical limit. In 2024, the University of Southampton cooperated with Microsoft to increase the transmission loss of DNANF in 1550 nm band to (0.08 ± 0.03) dB/km ^[18]. Subsequently, a research team in China achieved ultra-low loss below 0.10 dB/km by using a four-cell truncated double-nested structure. By 2025, FiberHome announced that the minimum attenuation is about 0.063 dB/km, and LongiTech said that the minimum loss of the institute is about 0.05 dB/km ^[19].

With the loss decreasing, the research focus of HC-ARF gradually shifts from exceeding the theoretical limit to practical application. Ultra-low loss not only reduces the number of optical amplifiers and relay stations, and reduces the system cost, but also increases the possibility of being used in submarine communication, intercontinental backbone network and ultra-long-distance optical transmission.

3.2 Ultra-low nonlinear distortion and low-latency transmission

Besides ultra-low loss, ultra-low nonlinearity and low transmission delay are two key advantages of hollow-core anti-resonant fibers (HC-ARF). Since most of the light power travels in the air core, the interaction between the light field and the glass material is significantly weakened, giving HC-ARF excellent nonlinearity suppression and low-delay properties. In terms of nonlinearity, the nonlinear refractive index of air is only about 10^{-3} to 10^{-4} that of silica, making the effective nonlinear coefficient of HC-ARF much lower than that of traditional single-mode fibers ^[20]. This means that at high input powers, it can effectively suppress nonlinear effects like the Kerr effect, self-phase modulation, cross-phase modulation, and four-wave mixing ^[21], improving the system's optical power tolerance, supporting high-order QAM modulation and high-capacity wavelength-division multiplexing transmission, while also reducing the complexity of digital signal processing (DSP) compensation and system power consumption. For delay, since the refractive index of air is close to 1, while silica is about 1.45, the transmission delay of HC-ARF is around 3.46 μ s/km, which is about 30%-31% lower than traditional single-mode fiber at around 5 μ s/km ^[22]. This makes it quite advantageous for low-latency scenarios like high-frequency trading in finance, data center interconnects, cloud computing, and AI cluster interconnections. In recent years, with the combined improvement of ultra-low loss, ultra-low nonlinearity, and low delay, HC-ARF has achieved broadband low-loss transmission covering the S, C, and L bands, and supports single-fiber transmission capacities over 100 Tbps, providing important support for next-generation ultra-high-speed, high-capacity optical communications. As specifically stated in Table 1.

Table 1. Latest Research Advances on Key Performance Properties of Hollow-core Anti-resonance Optical Fibers.

performance index	Current Level	Representative Achievements	Engineering Significance
Minimum Loss	≈ 0.05 dB/km	Changfei, Fenghuo, etc.	Ultra-long-distance communication
nonlinear	Three to four orders of magnitude lower than SMF	Multiple experimental validations have been conducted.	Supports high-power transmission
propagation delay time	≈ 3.46 μ s/km	Multiple System Experiments	Data Centers, Financial Communications
available bandwidth	S+C+L wave band	Broadband Verification	WDM system

Table 1. (continued) Latest Research Advances on Key Performance Properties of Hollow-core Anti-resonance Optical Fibers.

performance index	Current Level	Representative Achievements	Engineering Significance
Single Fiber Capacity	>100 Tbps	Latest System Experiment	Ultra-high-capacity communication

3.3 Air Separation Multiplexing Compatibility and Scalability

As the capacity of single-mode, single-core fiber optic communication gradually approaches the Shannon limit, space division multiplexing (SDM) is seen as an important way to break through the single-fiber capacity bottleneck ^[23]. By creating multiple independent spatial channels within the same fiber, SDM can linearly increase communication capacity and offers greater potential for capacity expansion compared to wavelength division multiplexing (WDM) and polarization division multiplexing (PDM). Multi-core fiber (MCF), as a key carrier for SDM, achieves parallel transmission by integrating multiple independent cores ^[24]. In recent years, hollow-core anti-resonant fibers (HC-ARF), with their air-core guiding mechanism and flexible microstructure design, have provided a new solution for space division multiplexing. Multi-air-core structures can further expand the spatial multiplexing dimensions while maintaining ultra-low loss, low latency, and extremely low nonlinearity; the weak mode coupling and low inter-core crosstalk between air cores also help improve the independence of spatial channels.

Now, hollow-core multi-core fibers is developing continuously. These designs refer to the research results of traditional multi-core fibers in crosstalk suppression, mode coupling control and amplification technology. And it is accelerating the connection between HC-ARF and SDM technology ^[25]. With the maturity of ultra-low loss HC-ARF, space division multiplexing has shifted from concept proof to system-level experiment bit by bit. Combining HC-ARF with WDM, PDM and high-order coherent modulation can further improve the transmission capacity and spectrum efficiency of a single optical fiber. At the same time, the International Telecommunication Union (ITU) began to formulate SDM-related standards, from basic research to industrial use.

4. KEY CHALLENGES FACED IN ENGINEERING APPLICATIONS

4.1 Precision Preparation and Geometric Tolerance Control

High precision manufacturing is the key to realize ultra-low loss transmission and large-scale application of hollow-core anti-resonant fibers (HC-ARF). Because HC-ARF has micron or submicron anti-resonant thin-walled structures, their geometric size, wall thickness uniformity and the accuracy of air-hole configuration directly affect the photoelectric field distribution and trapping loss. Therefore, it is a major topic in this field to maintain the consistency of microstructure between base material production and long-distance fiber drawing. At present, HC-ARF is mainly prepared by stack-and-draw method ^[26]. This process has important stages such as capillary processing, base material assembly, high temperature wire drawing, etc., all of which require very accurate capillary size and coaxiality. Even if the geometric deviations is very small, the state of anti-resonance will change, the scattering loss in the air-glass interface will also become larger, and the high-order mode suppression will also become larger. Therefore, the machining accuracy of capillary, the assembly consistency of preform and the real-time size control during wire drawing are important factors affecting the performance of HC-ARF. In recent years, high-precision drawing platforms, online size monitoring and smart closed-loop control technology have been gradually used in the production of HC-ARF ^[27]. However, geometric, ultra-low-loss HC-ARF still mostly relies on the precision manufacturing of lab scale, and the production efficiency, yield and batch consistency are still a problem for large-scale use. Fiber coating, preform preparation and post-processing technology also need to be better.

4.2 Welding encapsulation and system compatibility

In addition to the performance of optical fiber itself, the compatibility with system is an important factor limiting the practical application of hollow-core anti-resonant fibers (HC-ARF). Because HC-ARFs differ from traditional single-mode fibers in light-guiding mechanisms, mode-field distribution, and core structure, mismatches in mode, increased reflections, and reduced coupling efficiency can easily occur during connection, leading to higher system insertion loss. Currently, low-loss connections mainly rely on techniques like optimizing fusion splicing parameters, mode-conversion structures, and GIF transition sections to improve mode-field matching between HC-ARFs and conventional single-mode fibers ^[28]. While these methods have had some success, connection stability, repeatability, and long-term reliability still need

improvement. Moreover, existing devices like erbium-doped fiber amplifiers (EDFAs), optical switches, and wavelength-division multiplexers are primarily designed for solid-core fibers [29]. Due to differences in mode-field size, numerical aperture, and propagation modes, connecting HC-ARFs to current systems can still introduce extra coupling and reflection losses [30].

4.3 Reliability of long-distance transmission and engineering deployment

In recent years, hollow-core anti-resonant fibers (HC-ARF) have achieved ultra-low loss, ultra-low nonlinearity, and low-latency transmission, and are gradually entering the stage of real-world network testing. However, compared to mature solid-core fiber systems, their long-term operational reliability, environmental adaptability, and large-scale deployment capability still need further verification. Since they use a thin-walled air cladding structure, HC-ARF can easily experience micro-bending loss, polarization mode dispersion (PMD) changes, and additional mode coupling in complex environments like bending, vibration, temperature changes, and mechanical stress. Therefore, optimizing fiber coating materials, cable structures, and packaging processes to improve environmental adaptability is an important focus in current engineering research. In recent years, companies like Microsoft, Google, and AWS have carried out real-world tests of hollow-core fibers, confirming their feasibility for data center interconnects and high-speed communication networks. Domestically, companies like Changfei and FiberHome have produced HC-ARF over distances of more than twenty kilometers and have started demonstration applications in telecom operator networks and power communication systems, showing that HC-ARF is moving from lab research toward engineering validation. Despite ongoing industrial progress, HC-ARF still faces challenges like high manufacturing costs, limited mass production capacity, and an underdeveloped supporting industry chain. In the future, there's a need to strengthen material research, high-reliability cable design, long-term operational verification, and standardization in communication systems, while improving manufacturing equipment, connectors, and testing evaluation systems to promote large-scale commercial use of HC-ARF. As specifically stated in Table 2.

Table 2. Key Challenges and Development Directions in the Industrialization of Hollow-core Anti-resonance Optical Fibers.

Key Challenges	primal problem	research progress	Future Development Direction
precision manufactured	Geometric tolerance control is challenging.	Online monitoring; high-precision wire drawing	Intelligent manufacturing; digital wire drawing processes
Welded Packaging	Mode field mismatch, connection loss	GIMF transition; optimization of the welding process	Special connectors, low-loss packaging
System Compatibility	Insufficient compatibility with EDFA and related components	Research on New Types of Devices	Establishing a system of hollow-core communication devices
Long-term reliability	Micro-bending, PMD, Environmental stability	The ongoing field tests are progressing steadily.	Long-term reliability evaluation
Large-scale manufacturing	High cost and low yield	Construction of the pilot production line	Automation and batch production
standardization	Insufficient test specifications	The ITU continues to promote the standardization of related technologies.	Improve the industrial standard system

5. SUMMARY AND OUTLOOK

Hollow-core antiresonant fiber (HC-ARF), through its antiresonant light guiding mechanism, achieves ultra-low loss, ultra-low nonlinearity, and low latency transmission, overcoming the performance bottlenecks of traditional solid-core fiber in terms of transmission loss, propagation delay, and nonlinear effects. In recent years, with continuous advancements in structural design, fabrication processes, and system verification, HC-ARF transmission loss has been reduced to the order of 0.05 dB/km, achieving broadband, low-loss, and high-capacity transmission, providing a new technological path for next-generation high-speed optical communication.

Despite the significant progress made in HC-ARF, its engineering applications still face challenges such as manufacturing precision, system compatibility, long-term reliability, and large-scale production. Future efforts should focus on continuously optimizing the antiresonant structure design and fabrication process, promoting its deep integration with key technologies such as wavelength division multiplexing (WDM), space division multiplexing (SDM), and high-order coherent modulation, improving connection devices, amplifiers, and testing and evaluation systems, strengthening on-network verification and standardization, and accelerating the development of HC-ARF from laboratory research to engineering and commercial applications.

With the continuous growth in demand for high-speed, low-latency, and high-capacity transmission from emerging applications such as artificial intelligence computing networks, data center interconnection, 6G communication, and submarine optical cables, HC-ARF is expected to become an important transmission medium for next-generation optical communication networks. Driven by the synergistic development of technologies such as materials, structures, manufacturing processes, and system integration, it will achieve higher performance, lower cost, and wider engineering applications.

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