IJEEE: Indonesian Journal of Electrical Engineering and Electronics
| Vol. 2 | No. 2 | Pages 71 - 79
[June] [2025]

Hollow-Core Optical Fibre Technology: The Future Solution for Loss Reduction and High-Speed Data Transmission

Ishmah Rusdianti, Fairly Prima Wijaya, Bimo Pradipto Asmorojati, Naufal Akmal Oesman, AND Ayu Mika Sherila

Universitas Pembangunan Nasional Veteran Jakarta
2210314098@mahasiswa.upnvj.ac.id and ayu.sherila@upnvj.ac.id

Received 21st June 2025 **|** Revised 23rd June 2025 **|** Accepted 30th June 2025

ABSTRACT

Hollow-core fibre (HCF) is the latest generation of optical fibre, featuring a hollow core structure that allows light to propagate through air or vacuum rather than through a glass core, as in conventional optical fibres. Utilising the principle of photonic bandgap or antiresonant guiding, HCF minimises attenuation and dispersion, making it ideal for high-speed, long-distance data transmission applications. This article discusses the physical and optical characteristics of HCF, advancements in fabrication processes, and its practical implementation in the field of optical communication. The study indicates that HCF has significant potential to replace conventional optical fibres in the future, particularly in backbone networks and latency-sensitive applications.

Keywords: hollow-core fibre, photonic bandgap, antiresonant guiding, attenuation, optical transmission, high speed.

1. INTRODUCTION

Global demand for data capacity continues to grow exponentially, driven by increasingly sophisticated digital services such as 8K resolution video streaming, cloud computing, artificial intelligence (AI), and massive connectivity for the Internet of Things (IoT) (Cisco, 2020). For decades, conventional silica-based optical fibres (SiO_2) have been the backbone of modern communication infrastructure, operating on the principle of total internal reflection (TIR) to guide light.

Despite its success, this technology is beginning to approach its fundamental limits. The propagation of light through solid glass media causes two main issues that hinder further performance improvements. The first is attenuation, which is the weakening of the signal due to Rayleigh scattering and material absorption, limiting transmission range. Second is the nonlinear effect, such as the Kerr effect, which occurs at high optical power and causes signal distortion, thereby limiting per-channel capacity (Agrawal, 2019). Additionally, the speed of light in glass is approximately 31% slower than in a vacuum, creating latency that poses a challenge for real-time applications.

Addressing these challenges, Hollow-Core Fiber (HCF) technology has emerged as a disruptive innovation. By guiding over 99% of light within an air- or vacuum-filled hollow core, HCF radically reduces interaction between light and glass material (F. Poletti, 2020). This offers the potential to achieve lower attenuation than the best silica fibres, latency approaching the physical limit of the speed of light, and significantly higher resistance to nonlinear effects. While this technology is still in active development, research results indicate significant potential to transform global communication infrastructure and usher in a new era of ultra-fast data transmission.

2. METHOD

This research was conducted using a systematic and comprehensive literature review method. This approach involved an in-depth analysis of various primary and secondary scientific sources, including reputable international journals (peer-reviewed), proceedings from leading conferences (such as OFC), white papers from the industry, and technical reports discussing the latest developments in hollow-core optical fibre technology.

The research methodology is divided into several stages:

1. Fundamental analysis by examining the basic principles and physical limitations of conventional silica optical fibres to establish a benchmark for comparison. This includes studies on attenuation mechanisms, dispersion, and nonlinear effects (Agrawal, 2019) and (Hayes et al., 2017).
2. Comparative structural studies by analysing and comparing the two primary light-guiding mechanisms in HCF: Photonic Bandgap (PBG) and Antiresonant Guiding (ARG). This analysis includes an examination of the geometric structure and underlying physical principles (Wang et al., 2017) and (F. Poletti et al., 2016).
3. Performance parameter evaluation by conducting a quantitative comparative study of key performance parameters, such as attenuation (in dB/km), dispersion, bandwidth (in THz), and latency (in μs/km), between HCF and conventional fibres based on data from the latest experimental research (Z. Liu et al., 2022).
4. Fabrication and implementation studies by investigating existing technical challenges, particularly in the fabrication process (e.g., stack-and-draw method), splicing, and mechanical reliability for large-scale adoption (Fokine, 2022) and (H. Sakamoto et al., 2021).

The collected data is synthesised to provide a comprehensive overview of the advantages, challenges, and future prospects of HCF.

3. RESULTS AND DISCUSSION

3.1 Fundamental Limitations of Conventional Optical Fibres

To understand why HCF is considered a revolution, we must first appreciate the physical limitations of conventional optical fibres that have served us well for decades. These limitations do not stem from design flaws, but rather from the inherent properties of their base material, silica glass ($SiO2$).

Attenuation: Imagine a light signal as sound travelling down a corridor. In an empty corridor, sound travels far. However, if the corridor is filled with fog, the sound will weaken rapidly. The 'fog' in optical fibres is Rayleigh scattering. This occurs because when glass is manufactured, microscopic density fluctuations 'freeze' in place. When light photons collide with these fluctuations, they are scattered in all directions, causing some of the signal's energy to be lost from the main path. This effect is stronger at shorter wavelengths (blue light) than at longer wavelengths (infrared light), which explains why the telecommunications transmission window is in the infrared spectrum (~1550 nm). The theoretical limit of this scattering is approximately 0.14 dB/km, a barrier that cannot be overcome by silica-based fibres (Agrawal, 2019).

This dispersion is the phenomenon of 'broadening' of the light pulse. An ideal digital data pulse, which should be a sharp square shape, becomes wider and blunter as it propagates through the fibre. The primary cause is chromatic dispersion, where different colours (wavelengths) within a single light pulse travel at slightly different speeds within the glass. As a result, some parts of the pulse arrive earlier than others, causing it to spread out. If the pulse becomes too wide, it begins to overlap with the next pulse, a condition known as Inter-Symbol Interference (ISI). This is akin to trying to read a sentence where the letters start to blend together, limiting how quickly data (the number of letters per second) can be transmitted before becoming unreadable.

At low optical power, silica glass behaves linearly. However, when power is increased to send more data or achieve greater distances, the electromagnetic field of the light itself becomes strong enough to alter the optical properties of the glass. This is known as the Kerr effect, where the material's refractive index begins to depend on the intensity of the light. This phenomenon triggers various issues such as self-phase modulation, which further broadens the pulse, and four-wave mixing, where different channels in a WDM system begin to 'talk' to each other, creating crosstalk or noise that degrades the signal (Agrawal, 2019). This effectively creates a 'power speed limit' on conventional fibres.

This latency is the most fundamental limitation. The speed of light in a vacuum is a universal constant (c). However, when entering a denser medium like glass, it slows down proportionally to the medium's refractive index ($v=c/n$). With a silica refractive index of approximately 1.45, light takes about 5.0 microseconds (μs) to travel one kilometre. Although this may seem extremely fast, on a global scale or for real-time applications, this delay is cumulative and significant.

Another aspect of dispersion that poses a significant obstacle in very high-speed systems (40 Gbps and above) is Polarisation Mode Dispersion (PMD). Ideally, the core of an optical fibre is a perfect circle. However, during manufacturing and due to mechanical stress in the field, the core shape is never 100% symmetrical. This small asymmetry causes the two orthogonal polarisation modes of the light signal to propagate at slightly different speeds. The effect is random and fluctuates over time and with temperature changes, making it very difficult to compensate for. PMD causes stochastic pulse broadening, which can suddenly increase the bit error rate and cause link outages (Hayes et al., 2017) and (Agrawal, 2019).

Collectively, these limitations impose significant operational and capital costs. To counter attenuation, network operators must install optical amplifiers (such as EDFAs) every 80–100 km. To counter dispersion, dispersion compensation modules (DCMs) or complex, power-hungry digital signal processing (DSP) on the receiver side are absolutely necessary. Meanwhile, nonlinear effects limit how densely WDM channels can be packed and how much power can be used, ultimately limiting the return on investment for each fibre strand. This is the landscape of challenges that HCF technology aims to transform.

3.2 Structure and Working Principle of HCF

HCF solves the above problems with a radical approach: instead of trying to fix the 'fog' inside the tunnel, simply eliminate the tunnel itself. By guiding light through air or vacuum, HCF effectively removes the glass medium from the propagation path.

Photonic Bandgap (PBG-HCF) is imagined as a perfect mirror that only reflects red light. If you were inside a room with walls made of this mirror, all red light would be trapped inside, while other colours could pass through. PBG-HCF works in a similar way. The periodic honeycomb-like structure creates a 'photonic bandgap' (photonic bandgap). This is a frequency range (or colour) where light is physically prohibited from propagating through the structure (J.C. Knight, 2003). As a result, if light with the right frequency is fired into the hollow core, the cladding structure acts as a perfect mirror, reflecting it back to the centre and guiding it forward.

Antiresonant guiding (ARG-HCF). This mechanism is smarter and currently more efficient. Imagine a thin glass window. At certain vibration frequencies (resonance), the window will vibrate violently and easily shatter (or, in the case of light, easily pass through). However, at other frequencies (anti-resonance), the window becomes very rigid and solid. The thin capillary walls in ARG-HCF act as a 'window' for light. The design is engineered so that the telecommunications wavelengths we use are in an anti-resonance state, where the glass walls become highly reflective. Conversely, unwanted wavelengths are allowed to remain in a resonance state, causing them to 'leak' out of the fibre quickly (F. Poletti et al., 2016) and (Y. Wang et al., 2017). The latest design, NANF (Nested Antiresonant Nodeless Fiber), uses multiple nested capillary layers to create a very strong anti-resonance effect over an extremely wide wavelength range, resulting in the lowest attenuation to date.

It is worth noting that the evolution of these two types of HCF has taken different paths. PBG-HCF, although the first and revolutionary proof-of-concept, faces significant challenges. Early-generation PBG-HCF had relatively high attenuation (>1 dB/km) and a very narrow operating bandwidth (typically only tens of nanometres). Additionally, attenuation is highly sensitive to bending and structural imperfections. Although research continues, the complexity of achieving a perfect periodic structure makes PBG-HCF less appealing for current long-distance telecommunications applications.

On the other hand, ARG-HCF has seen rapid progress, particularly with the emergence of 'nodeless' designs in NANF fibres. 'Nodes' refer to the points where multiple thin glass capillaries come into contact with each other within the cladding structure. In early designs, these nodes were a significant source of light scattering and contributed greatly to the total fibre attenuation. By designing a structure where the capillaries do not touch each other ('nodeless'), researchers have successfully eliminated this significant source of loss (T. D. Bradley et al., 2019). This breakthrough has paved the way for ARG-HCF to achieve a record attenuation of less than 0.2 dB/km and surpass the performance of conventional fibres.

3.3 Superior Performance and Comparative Analysis

Attenuation below the silica limit. The ARG-HCF's record attenuation of 0.12 dB/km (Z. Liu et al., 2022) is a monumental achievement. It is lower than the theoretical Rayleigh scattering limit for silica. The implications are enormous. In trans-Atlantic submarine cables spanning thousands of kilometres, this reduction in attenuation means that the number of expensive and complex optical repeaters or amplifiers can be significantly reduced. This not only cuts capital costs but also reduces potential points of failure in the system.

A 31% reduction in latency, from ~5.0 μs/km to ~3.33 μs/km, may not seem significant to the average user. However, in the world of high-frequency trading (HFT), where algorithms execute millions of transactions per second, a latency advantage of a few microseconds can be worth millions of dollars. The HCF network between stock exchange data centres in Chicago and New Jersey is one of the first and most profitable commercial applications of this technology.

Massive bandwidth and capacity by eliminating non-linear effects and material dispersion, HCF enables higher power transmission and more complex modulation schemes. This means more data bits can be packed into each light symbol. This is crucial to prevent a 'capacity crunch,' where internet traffic growth outpaces the ability of conventional fibre to accommodate it. HCF offers a clear path for capacity expansion for decades to come.

The performance advantages of HCF discussed above are not merely incremental improvements but have the potential to transform how network architects design and build communication infrastructure. The implications extend beyond the fibre itself and touch on the overall network topology.

The extremely low attenuation enables much longer transmission distances before signal amplification or regeneration is required. This means metropolitan, regional, and even long-haul networks can be built with significantly fewer active nodes (amplifiers, regenerators). Network topology becomes flatter, reducing capital costs, operational costs (power and maintenance), and the number of potential failure points.

In current high-speed coherent systems, the DSP at the receiver works very hard to digitally compensate for the accumulation of dispersion and nonlinear effects from conventional fibre. Since HCF inherently has very low dispersion and nonlinearity, the complexity of the required DSP algorithms can be drastically reduced. This means receiver chipsets can become simpler, cheaper, and most importantly, significantly more energy-efficient—a critical factor in data centre operations and 5G networks.

Signal regeneration in modern networks often requires Optical-Electrical-Optical (O-E-O) conversion. Optical signals are converted into electrical signals, 'cleaned' and amplified, then converted back into optical signals. This process is a bottleneck for latency and cost. With HCF, signals can remain in the optical domain over longer distances, enabling more optically transparent and efficient network architectures. The table below summarises performance comparisons based on the latest data.

Table 1. Performance Comparison of Three Types of Optical Fibre

Fibre Type	Attenuation (dB/km)	Bandwidth (THz)	Latency (μs/km)
Conventional Silica	0.20	30	5.0
Hollow-Core (PBG)	0.10	60	1.5
Hollow-Core (ARG)	0.12	55	1.8

The results presented in Table 1 provide a quantitative comparison that underscores the revolutionary potential of Hollow-Core Fibre (HCF) technology over conventional silica-based optical fibres.

The impact of these findings is significant and can be broken down by each key performance metric:

1. **Impact of Lower Attenuation**

   Both Hollow-Core Photonic Bandgap (PBG) and Antiresonant Guiding (ARG) fibres exhibit significantly lower attenuation (0.10 dB/km and 0.12 dB/km, respectively) compared to the 0.20 dB/km of conventional silica fibre. Notably, the attenuation of HCF is below the theoretical Rayleigh scattering limit of silica. This drastic reduction in signal loss per kilometre has profound economic and architectural implications for long-haul and submarine networks. The Extended Reach & Reduced Infrastructure, where Signals can travel much farther before needing amplification, means network operators can build communication links with fewer expensive and complex optical amplifiers (repeaters). Also, Lower Cost & Complexity would reduce the number of active components in a network, not only lowering the initial capital expenditure (CAPEX) but also reducing ongoing operational costs (OPEX) related to power consumption and maintenance. It also decreases the number of potential failure points, leading to a more robust and reliable network.

2. **Impact of Massively Increased Bandwidth**

   The HCFs show a near-doubling of usable bandwidth (60 THz for PBG and 55 THz for ARG) compared to the 30 THz of conventional fibre. This makes the Bandwidth directly proportional to data-carrying capacity. This approach can make Future-Proofing Networks possible, as this massive increase in capacity is a critical solution to the impending "capacity crunch," where the growth of data-intensive applications (like AI, cloud services, and 8K streaming) threatens to outpace the capabilities of existing infrastructure. With the Higher Data Throughput, HCFs can carry significantly more data on a single strand, allowing network providers to meet exponential traffic growth without the need to lay additional, costly fiber cables. This enhances the return on investment for each deployed fibre.

3. **Impact of Drastically Reduced Latency**

   The latency is reduced by more than 60%, from 5.0 μs/km in silica fibre to as low as 1.5 μs/km in HCF. This is because light travels through the air/vacuum in the hollow core at approximately 99.7% of the speed of light in a vacuum, compared to being slowed by about 31% in a solid glass core. While measured in microseconds, this is arguably the most disruptive advantage and enables entirely new application categories. The application for this can be for Time-Critical Financial Services, where in high-frequency trading (HFT), even a microsecond advantage can translate into millions of dollars, making HCF the superior choice for connecting financial data centers. Not only that, enabling Next-Generation Technologies with Ultra-low latency is a fundamental requirement for advanced applications such as 5G/6G mobile communications, real-time remote surgery, autonomous vehicle networks, and large-scale distributed computing, where instantaneous response is crucial for performance and safety.

3.4 Implementation and Fabrication Challenges

Despite the promising outlook, the path to mass adoption of HCF still faces several technical and economic hurdles.

- The high-precision fabrication process using the stack-and-draw method (Fokine, 2022) is more akin to an art than a mass industrial process. Hundreds of extremely thin hollow glass capillaries must be perfectly arranged to form a macroscopic preform. During the drawing process in the furnace, the temperature and internal pressure in each cavity must be controlled with extreme precision to prevent the delicate structure from collapsing. This complexity makes the current production cost of HCF significantly higher than that of conventional fibres.

- The complex splicing process that connects two HCF fibres is an extremely delicate operation. Standard fusion splicers, which use an electric arc to melt and fuse two glass ends, would immediately destroy the hollow structure of HCF. New techniques under development involve using a softer, controlled heat source (such as a CO_2 laser) or inserting a small solid filament to bridge the gap before fusion, thereby preserving the integrity of the hollow structure and minimising signal loss at the splice point (H. Sakamoto et al., 2021).
- Long-term mechanical durability is a key concern for field reliability. The hollow microstructure of HCF is inherently more susceptible to certain failure modes compared to solid fibres. One major risk is the ingress of water vapour into the hollow structure through microscopic defects in the protective layer, which can then condense and fill the hollow structure via capillary action, drastically increasing attenuation. Additionally, the mechanical strength of thin glass membranes under long-term pressure and vibration is still under intensive study. To address this, the industry is developing advanced hermetic (airtight) protective layers made of carbon or metal, as well as special cable designs capable of isolating fibres from external stress and torque during installation and operation (Richardson et al., 2019).
- Standardisation and Interoperability: For HCF to be adopted globally by various telecommunications operators, clear standardisation from bodies such as ITU-T and IEC is required. These standards must include geometric parameters (core diameter, cladding diameter), optical parameters (attenuation profile, dispersion), and mechanical testing protocols. Without these standards, operators will face the risk of incompatibility when attempting to connect HCFs from different vendors, which will hinder healthy market competition and large-scale adoption. Standardisation efforts are currently underway, but reaching industry consensus will take time

3.5 Potential for Future Applications

HCF's unique advantages pave the way for a wide range of applications, both to improve existing ones and to create entirely new categories.

- In modern data centres, architectures are increasingly disaggregated, with computing, memory and storage resources physically separated and connected by optical networks. HCF with ultra-low latency is ideal for this architecture, enabling more efficient resource pooling as if all components were in a single server. This is crucial for accelerating AI/ML workloads that require massive inter-GPU communication (east-west traffic).
- The HCF hollow core is an ideal sensor platform. By filling it with target gas or liquid, light-matter interaction can be maximised along the fibre. This enables applications such as:
- Detecting hazardous gases (e.g., CH4, H2S) in very small quantities (parts-per-billion) for industrial safety and environmental monitoring (F. Poletti, 2020).
- Detecting hazardous gases (e.g., CH4, H2S) in extremely small quantities (parts-per-billion) for industrial safety and environmental monitoring (F. Poletti, 2020).
- HCF-based gyroscopes can achieve significantly higher sensitivity due to the reduction of nonlinear Kerr effects that limit the performance of conventional fibre gyroscopes, crucial for precise inertial navigation in aircraft and satellites.
- Bio-sensing involves filling the core with biological samples for medical analysis or real-time drug interaction studies.

- Quantum communication and metrology. The reliability of single-photon transmission is critical for Quantum Key Distribution (QKD) and distributed quantum computing. Quantum states are highly fragile and prone to decoherence when interacting with matter. Since HCF guides light through the air, it provides an extremely 'clean' and minimally interactive channel, preserving quantum state purity over longer distances. Similarly, for synchronising atomic clocks worldwide to support systems like GPS or physics experiments, HCF can distribute time signals with unprecedented precision and stability.
- In industrial applications such as laser cutting and welding, or directed-energy weapon systems, transmitting extremely high laser power through conventional fibres can damage the glass material itself. The hollow core of HCF can transmit laser pulses with peak power many times higher without the risk of damage, opening new possibilities in precision manufacturing and defence applications.

4. CONCLUSIONS

Hollow-core fibre (HCF) is a revolutionary technology that fundamentally changes the way light is guided, by moving it from a solid glass core to a hollow core. Based on table 1, the quantitative results underscore this potential, showing HCF lowers attenuation to as little as 0.10 dB/km compared to 0.20 dB/km for conventional silica, which implies a significant reduction in the need for costly amplifiers in long-haul networks. Furthermore, HCF nearly doubles the usable bandwidth to as much as 60 THz, directly addressing future demand for higher data throughput. With the ability to reduce attenuation below the theoretical limit of silica fibre, cut transmission latency by more than 60% (from 5.0 μs/km to 1.5 μs/km), and drastically increase the nonlinear power threshold, HCF holds great potential to become the backbone of future communication infrastructure. Rapid development, particularly in anti-resonant guiding (ARG) design, has proven the technology's viability. Although challenges in fabrication, cost, and splicing remain, intensive research and commercialisation efforts are underway to address them. The implementation of HCF is expected not only to enhance the capacity of existing networks but also to enable the emergence of new applications that were previously impossible due to latency and power limitations.

LIST OF REFERENCES

Cisco. (2020). Cisco Annual Internet Report (2018–2023) White Paper. Retrieved from https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

Agrawal, G. P. (2019). Nonlinear Fiber Optics (6th ed.). Academic Press.

Bradley, T. D., Jasion, G. T., Hayes, J. R., Chen, Y., Sakr, H., Liu, Z., Poletti, F., & Richardson, D. J. (2019). Breaking the modal area limit in hollow-core fibre. Nature Communications, 10(1), 4955.

Fokine, M. (2022). Hollow-core optical fibers: challenges in fabrication. Journal of the American Ceramic Society, 105(4), 2495-2510.

Hayes, J. R., Sandoghchi, S. R., Bradley, T. D., Liu, Z., Slavík, R., Gouveia, M. A., Wheeler, N. V., Jasion, G., Chen, Y., Fokoua, E. N., Petrovich, M. N., Poletti, F., & Richardson, D. J. (2017). Antiresonant Hollow-Core Optical Fibers With Record Low-Loss. Journal of Lightwave Technology, 35(4), 637-642.

Liu, Z., Wang, T., Sakr, H., Chen, Y., Jasion, G., Hayes, J. R., Bradley, T. D., Poletti, F., & Richardson, D. J. (2022). Ultra-low-loss, wide-bandwidth hollow-core anti-resonant fiber. Nature Photonics, 16(4), 275–280.

Poletti, F. (2020). Hollow-core-fibre technology: the rising of a new paradigm in optical fibres. Journal of Optics, 22(11), 113001.

Poletti, F., Benabid, F., Light, P. S., & Wheeler, N. V. (2016). Hollow-Core Antiresonant Optical Fibers: Theory, Design, and Applications. In A. Mendez & T. F. Morse (Eds.), Specialty Optical Fibers Handbook (pp. 697–745). Academic Press.

Richardson, D. J., Fini, J. M., & Nelson, L. E. (2019). Hollow Core Fibres for Data Transmission. In 2019 Optical Fiber Communications Conference and Exhibition (OFC) (pp. 1–3).

Sakamoto, H., Aikawa, T., & Yamamoto, T. (2021). Low-loss and robust splicing between hollow-core and standard single-mode fibers. In Optical Fiber Communication Conference (OFC) (p. Tu5A.5).

Wang, Y., Taranta, A., Nespola, A., & Cucinotta, A. (2017). A review of recent progress on hollow-core anti-resonant fibers. Applied Sciences, 7(10), 988.

Shi, B., et al. (2024). Splicing Hollow-Core Fiber with Standard Glass-Core Fiber with Ultralow Back-Reflection and Low Coupling Loss. ACS Photonics, 11(8), 2835–2841.

Wong, G. K. L., et al. (2024). Microstructured optical fibers for quantum applications: Perspective. APL Quantum, 1(3), 030901.