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Opportunities and Challenges of Hollow Core Fiber Deployment in India

Parvez Khan, Soham Parulekar, Nazam Perwar
Independent Researcher

ABSTRACT

As the telecommunications backbone of India rapidly scales to support expansive 5G/6G rollouts, high-frequency financial trading networks, and the explosive growth of AI-driven hyperscale data centers, our reliance on conventional single-mode fiber (SMF) faces physical limitations. Hollow Core Fiber (HCF), which guides light through an air-filled or vacuum core rather than solid silica glass, represents a paradigm shift in optical networking. This paper evaluates HCF's technical maturity, assessing its strategic opportunities for operations in India against formidable deployment barriers, such as a 50-100x cost premium, highly specialized splicing requirements, and a high terrestrial disruption environment. A phased deployment strategy tailored to the Indian telecom landscape is outlined.

KEYWORDS- Hollow Core Fiber (HCF), Single Mode Fiber (SMF), Optical Fiber, Ultra-Low Latency Networks Communication

I INTRODUCTION

The advances in hollow-core fibers (HCFs) have been substantial in recent years, emerging as a promising new fiber technology that can replace traditional silica fibers in the future [1]. The first main advantage of this fiber type is the potential to decrease the attenuation profile, which nowadays is around 0.21 and 0.17 dB/km for standard single-mode fiber (SSMF) and pure-silica-core fiber (PSCF), respectively, to values below 0.11 dB/km [2] and potentially even lower. Besides lower attenuation values, HCF also presents a potentially wider spectral low-loss region, making the adoption of ultra-wide band (UWB) [3] transmission systems more attractive. Furthermore, HCFs have a low nonlinearity and negligible stimulated Raman scattering (SRS) [4], which allows the transmission of channels with higher power without signal degradation. In silica-based fibers, SRS, which induces power transfer from higher to lower frequencies, requires a careful and complex power optimization in UWB transmission [5]. In the absence of SRS, power optimization in these transmission systems is greatly simplified. Finally, light is transmitted 50% faster through HCF due to its near-vacuum medium [6]. Therefore, the latency presented by this fiber type is around 33% lower than SSMF/PSCF, which makes it suitable for latency-constrained applications. With all the aforementioned advantages, HCF deployment is envisioned across a wide range of applications, from data center interconnect (DCI) to ultra-long-haul optical networks.

Importantly, despite all the advantages of HCF, some drawbacks and uncertainties need to be addressed or properly considered/managed in order for this fiber type to compete and potentially outperform traditional solid core fibers. Firstly, exploiting the ability to launch high signal powers into HCF requires the availability of optical amplifiers with a high maximum total output power. Key parameters, such as the noise figure and complexity/cost of these devices, are paramount to leverage this benefit of HCF. Secondly, an additional penalty, negligible in silica fibers, is theinter-modal interference (IMI), which consists of the lossinduced by high-order modes in the fundamental mode. It has been shown that IMI has no meaningful impact in performance if it is below −60.0 dB/km [7]. Still, IMI values between −40.0 and −55.0 dB/km have been considered in previous works [**2**,**4**,**8**]. In view of the uncertainty around the large-scale production of HCF and the properties of these fibers, a range of IMI values should be considered when reporting system-level analysis. Another aspect that requires consideration involves the larger connection losses, such as fiber splices and interconnection with solid-core fibers. The former loss is required, e.g., in the event of fiber cuts, while the later need to be considered for HCF deployment as the whole optical environment of components, e.g., erbium-doped fiber amplifiers (EDFA) and reconfigurable optical add-drop multiplexers (ROADM), was developed for traditional fiber types. These losses have been decreasing, with the latest record set at 0.18 dB per splice [**9**].

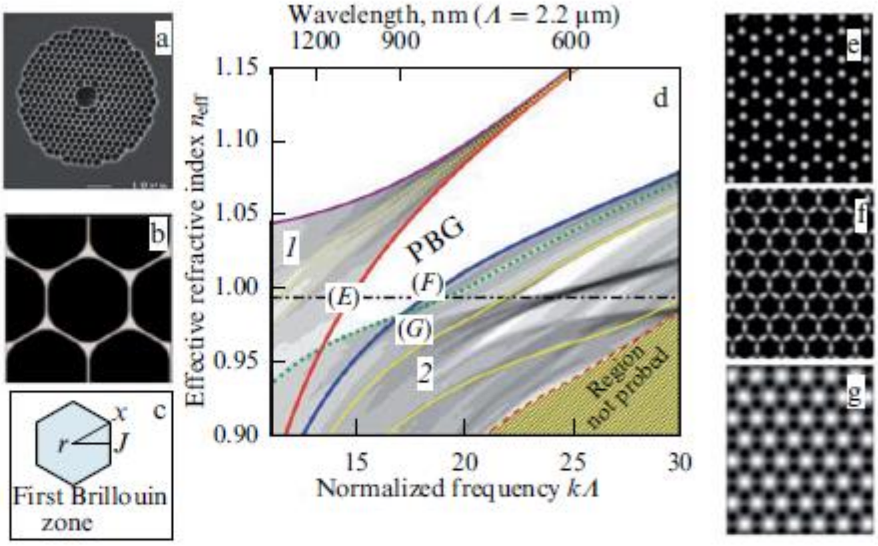

Figure 1. (a) Cross section of a photonic-crystal HCF; (Benabid F)

Hollow Core Fiber (HCF)

For four decades, the Indian telecom sector has relied heavily on conventional silica core optical fibers (such as G.652 and G.654), which guide light via total internal reflection. However, quartz glass imposes inherent capacity bottlenecks, performance limits, and latency constraints, operating at roughly two-thirds the speed of light in a vacuum. HCF technology, specifically designed utilizing Nested Anti-Resonant Nodeless Fiber (NANF) and Double-Nested NANF (DNANF), confines light within an air core using microstructured glass tubes that act as wavelength-selective mirrors. Because light travels through air, it propagates at 99.7% of the speed of light in a vacuum, drastically reducing latency while minimizing the signal's interaction with the glass material. Recent global trials and research demonstrate HCF's feasibility for latency-critical applications and long-distance transmission, highlighted by Microsoft's acquisition of Lumenisity and its deployment of over 1,280 km of live Azure HCF [10].

Technical Superiority of HCF over SMF: The transition from SMF to HCF provides non-incremental physical advantages. It offers a fundamentally different approach to optical signal propagation, promising near-vacuum-speed transmission and near-zero nonlinear effects.

Table 1: Technical Performance Comparison (HCF vs. Conventional SMF)

Parameter	Conventional SMF (G.652)	HCF – Lab Potential	HCF – Current Real-World Status	Practical Implication for Telcos
Latency	~4.9 µs/km	~3.3–3.5 µs/km (~30% lower)	~3.5–3.8 µs/km (deployment-dependent)	Meaningful advantage for ultra-low latency use cases (e.g., HFT, 5G fronthaul), but limited by deployment scale
Attenuation (C-band)	~0.14–0.20 dB/km	As low as ~0.05 dB/km (research record)	~0.08–0.15+ dB/km typical	Comparable to SMF in best cases, but consistency and scalability still evolving
Nonlinear Coefficient	~1.3 $W^{-1}\cdot km^{-1}$	~0.001 $W^{-1}\cdot km^{-1}$ (orders lower)	Very low, but system-limited gains	Enables higher launch power and simpler system design, but not yet fully exploited commercially
Chromatic Dispersion	~17 ps/nm·km	~2–5 ps/nm·km (design-dependent)	Low but variable by fiber type	Reduces DSP complexity and power consumption in coherent systems
Usable Bandwidth	~10 THz (C+L band)	Potentially >18 THz (S+C+L and beyond)	Limited by amplifiers/components	Future-proofing potential, but ecosystem not mature yet
Cost per Meter	~$0.05–0.10 (volume)	Not applicable	~$5–$10 (early-stage)	Major barrier; restricts use to niche/high-value routes

Strategic Opportunities in the Indian Market: While replacing India's vast existing SMF infrastructure is neither feasible nor necessary, targeted deployment of HCF opens up high-margin revenue streams [11].

- **Hyperscale Data Center Interconnects (DCI):** India is seeing a massive surge in AI data centers, evidenced by industry events like the upcoming "DCD>Connect | India 2026". Currently, latency limits interlinked data centers to a 60-80 km radius. HCF expands this radius to 90-120 km. In power-constrained metros like Mumbai, Chennai, and Delhi NCR, this allows operators to build facilities further out where land and power are available while meeting strict latency targets.

- **High-Frequency Trading (HFT):** Financial institutions in hubs like Mumbai and GIFT City (Gujarat) rely on microsecond advantages. Providing an ultra-low latency dark fiber service connecting Indian financial hubs represents a massive monetization opportunity.
- **5G/6G Fronthaul:** Strict protocol timeouts on 5G networks restrict the distance between central offices and radio masts. In India's sprawling cities, HCF can extend this reach by 50%, serving more radio masts from a single centralized hub and radically improving 5G deployment economics.

Data derived from integrated techno-commercial modelling.

The Indian Operational Reality & Deployment Challenges: Despite its multiple advantages, HCF is currently rated "Conditionally Ready" and faces severe deployment barriers before it can be integrated into network backbones.

- **Fiber Cut Incidence and Restoration:** India’s high fiber cut incidence is primarily driven by uncoordinated excavation and civil works. The Department of Telecommunications (DoT) has officially estimated nearly 10 lakh (1 million) optical fiber cuts annually, largely due to excavation and construction activity, with economic losses of approximately ₹3,000 crore per year as per DOT press release “Measures to prevent damage to underground telecom infrastructure” (2022)
- **Splicing Complexity:** Standard SMF installation practices are insufficient. HCF splicing requires an average of 15-25 minutes compared to 5-7 minutes for SMF. Splicing requires extremely expensive, specialized alignment machines equipped with "Ring-of-Fire" technology, as traditional splicing melts the microstructures.
- **Environmental Vulnerabilities:** HCF is up to 10 times more sensitive to bending, requiring thicker cables, and a broken cable invites environmental moisture/dust that instantly degrades the hollow core.
- **Testing Limitations:** Testing an HCF link with an Optical Time Domain Reflectometer (OTDR) is highly complex due to the Rayleigh Backscattering (RBS) being ~30 dB lower than in SMF. However, few vendors have launched an all-in-one HCF testing platform recently, though widespread field expertise in India remains nonexistent.
- **Lack of Standardization:** Unlike the mature G.652/G.654 series, there are currently no ITU-T standards for HCF, leading to proprietary, non-interoperable designs from different vendors [12-13].

Techno-Economic and Policy Implications: At current pricing, a full-route HCF CAPEX can be approximately 50–100x the SMF equivalent, reflecting fiber cost dominance and line system adaptation. Under current economics, only ultra-low latency corridors (e.g., financial trading) may justify deployment based on premium potential [14]. The introduction of the Indian Telegraph (Infrastructure Safety) Rules, 2022, underscores the systemic vulnerability of India’s telecom infrastructure to excavation-related damage. Policy effectiveness directly influences techno-commercial feasibility. The creation of designated low-disruption corridors (e.g., financial trading routes, hyperscale inter-DC paths) with enhanced civil protection measures could provide early deployment zones for HCF [15].

Roadmap for HCF Adoption in India: Given the constraints and opportunities, the following is tentative phased timeline for HCF adoption in the network:

Table 2: HCF Operational Maturity &tentative Deployment Timeline for India

Timeframe	Global Milestone	Indian Telecom Industry tentative Adoption
2026-2028	Multi-hyperscaler production maturity; VIAVI tools deployed.	**Phase 1 (Lab Evaluation):** Partner with global vendors (e.g., YOFC, Lightera) and academic institutions for controlled trials.
2028-2030	ITU-T study groups established; target costs hit \$1-\$2/meter.	**Phase 2 (Targeted Premium DCI):** Deploy HCF on specific, latency-critical routes (e.g., connecting AI data centers or HFT nodes in Mumbai/GIFT City).
2032-2035	Full cost parity with premium SMF; standardized splicing & testing ecosystem.	**Phase 3 (General Metro Adoption):** Gradual rollout into metro networks and 6G fronthaul, where capacity and low non-linearity are required.

Table 2 outlines a phased roadmap for the operational maturity and deployment of Hollow Core Fiber (HCF) technology, aligning global advancements with tentative implementation timeline of adoption in the Indian telecom sector. During the 2026–2028 timeframe, global developments are expected to reach multi-hyperscaler production maturity with the deployment of advanced testing tools. In parallel, India is projected to initiate Phase 1 (Lab Evaluation), focusing on controlled trials through collaborations with global technology vendors like YOFC, Lightera as well as academic institutions such as the University of Southampton, Delhi. This phase aims to assess feasibility, performance, and compatibility within the Indian telecom environment.

In the 2028–2030 period, international standardization efforts are anticipated to strengthen, with ITU-T study groups formalizing frameworks and production costs reducing to approximately \$1–\$2 per meter. Correspondingly, India is expected to move into Phase 2 (Targeted Premium Data Center Interconnect - DCI Deployment), where HCF will be deployed in high-value, latency-sensitive applications. These may include critical infrastructure such as AI data centers and high-frequency trading (HFT) networks in key locations like Mumbai and GIFT City, where ultra-low latency provides a competitive advantage.

Looking further ahead to 2032–2035, HCF technology is projected to achieve full cost parity with premium Single Mode Fiber (SMF), along with the development of standardized splicing and testing ecosystems. At this stage, India is expected to enter Phase 3 (General Metro Adoption), involving broader integration of HCF into metropolitan telecom networks and emerging 6G fronthaul systems. This phase emphasizes large-scale deployment to support high-capacity data transmission, reduced signal distortion, and improved network efficiency, positioning HCF as a critical component in next-generation communication infrastructure.

Table 3: Comprehensive Performance Comparison (HCF vs. SMF)

Parameter	Conventional SMF (G.652)	Hollow Core Fiber (AR-HCF)	HCF Advantage
Attenuation (C-Band)	0.14 - 0.20 dB/km	0.05 - 0.11 dB/km (record/lab)0.085 - 0.28 dB/km (deployed)	Surpasses the Rayleigh limit of glass
Latency	4.9 µs/km	3.35 µs/km	1.54 µs/km saving (~31% reduction)
Group Refractive Index	1.468	1.003	Light travels at 99.7% of vacuum speed
Chromatic Dispersion	17 ps/nm·km	2-4 ps/nm·km	4-8x lower; reduces DSP complexity
Nonlinear Coefficient	1.3 $W^{-1}km^{-1}$	~0.001 $W^{-1}km^{-1}$	~1000x lower; enables higher launch power
Splice Loss	<0.05 dB (routine)	0.04-0.16 dB (HCF-HCF)0.15-0.3 dB (HCF-SMF)	SMF still superior; HCF rapidly improving
Bandwidth	C+L band (~10 THz)	18+ THz (S+C+L or broader)	1.8x wider usable spectrum
Damage Threshold	1-2 W continuous	>3 W demonstrated (34.8 dBm)	Enables ultra-high-power transmission
Temperature Sensitivity	7.5 ppm/°C (Shupe constant)	~0.52 ppm/°C	14x better thermal stability
Cost per Meter	$0.10 (volume)	$5-10 (current commercial)	HCF(50-100x) costlier

Table 3 presents a detailed comparison between Conventional Single-Mode Fiber (SMF - G.652) and Hollow Core Fiber (HCF - Anti-Resonant HCF) across key physical and performance parameters. The comparison highlights the significant technological advantages of HCF over traditional optical fiber systems, particularly in high-speed and low-latency communication applications.

In terms of attenuation, HCF demonstrates lower loss values (as low as 0.05 dB/km in laboratory conditions), surpassing the fundamental Rayleigh scattering limit of glass fibers used in SMF. This indicates the potential of HCF for long-distance transmission with reduced signal degradation. One of the most critical advantages is observed in latency, where HCF achieves approximately 3.35 µs/km compared to 4.9 µs/km in SMF, resulting in nearly a 31% reduction. This improvement is primarily due to the significantly lower group refractive index of HCF (~1.003), allowing light to travel at approximately 99.7% of the speed of light in vacuum, unlike SMF, where light propagates through glass.

HCF also offers superior performance in terms of chromatic dispersion, with values 4 to 8 times lower than SMF. This reduction minimizes signal distortion and decreases the need for complex digital signal processing (DSP). Furthermore, the nonlinear coefficient of HCF is approximately 1000 times lower than that of SMF, enabling higher optical power transmission without nonlinear impairments, which is crucial for high-capacity communication systems.

However, certain challenges remain. For instance, splice loss in HCF is still higher compared to SMF, especially when connecting HCF to SMF, although ongoing research is improving this aspect. In terms of bandwidth, HCF supports a significantly wider usable spectrum (18+ THz), nearly 1.8 times greater than SMF, making it suitable for next-generation ultra-high bandwidth applications.

Table 4: Record-Low Attenuation Achievements in HCF Across Key Wavelengths

Wavelength / Band	Record Attenuation (dB/km)	Fiber Type	Institution
1550 nm (C-Band)	0.05	AR-HCF	YOFC
1560 nm (C-Band)	0.174	DNANF	Univ. of Southampton
1550 nm (C-Band)	0.11	DNANF	Univ. of Southampton
1625 nm (L-Band)	0.22	NANF	Univ. of Southampton
1300 nm	0.22	DNANF	Univ. of Southampton
850 nm	0.33	DNANF	Univ. of Southampton
660 nm (Visible)	2.85	NANF	Research (Surface Scattering Reduction)

Table 4 presents a projected timeline for the commercialization and adoption of HCF across different networking domains. Between 2024 and 2026, HCF is expected to achieve maturity in hyperscaler and high-frequency trading applications. From 2026 to 2028, multi-vendor evaluations and early standardization efforts will expand its use in premium data center interconnects. By 2028–2030, standardized deployments and cost reductions will enable broader adoption by service providers. Between 2030 and 2033, HCF is expected to enter metro networks, followed by mainstream deployment in long-haul and submarine networks after 2033. This roadmap highlights a gradual transition from niche applications to widespread adoption as costs decrease and technology matures [16].

Table 5: Splicing and Restoration Operational Metrics. Given India's high fiber cut environment, the operational disparity in splicing and restoration between SMF and HCF is a crucial metric**.**

Parameter	SMF	HCF (Current)
Typical splice time	5–7 min	15–25 min

Rework probability	Low	Higher
Technician familiarity	High	Low

Table 5 compares the operational performance of Single-Mode Fiber (SMF) and Hollow Core Fiber (HCF) in terms of splicing and restoration, which is particularly critical in India due to frequent fiber cuts. The table shows that SMF has a clear advantage in operational efficiency, with a typical splice time of 5-7 minutes compared to 15-25 minutes for HCF. Additionally, SMF has a lower rework probability and higher technician familiarity, whereas HCF currently faces challenges due to limited field experience and specialized handling requirements. These factors highlight that although HCF offers superior transmission performance, its operational maturity is still evolving, and improvements in training and tools are necessary for large-scale deployment [17].

Table 6: Relative CAPEX Cost Modelling. This table outlines the capital expenditure multipliers required to deploy HCF relative to a standard SMF baseline (SMF baseline = 1).

Component	Relative Cost vs. SMF
Fiber	50–100×
Installation	3–4×
Closures	2×
Line system adaptation	1.5–2×

Table 6 presents a comparative analysis of the capital expenditure (CAPEX) required for deploying HCF relative to a standard SMF baseline. The results indicate that HCF deployment is significantly more expensive, with fiber costs ranging from 50 to 100 times higher than SMF. Installation costs are also elevated by 3–4 times, while closures and line system adaptations require 2× and 1.5–2× higher investment, respectively. This substantial cost difference is one of the major barriers to widespread HCF adoption and suggests that its deployment is currently viable only in high-value, performance-critical applications [18].

Table 7: Market Segmentation Viability in India. This table breaks down the economic justification for deploying HCF across different Indian telecommunications segments based on current costs.

Segment	Viability
High-Frequency Trading	High
Hyperscaler DCI	Medium
AI/ML clusters	Medium
Mobile Backhaul	Low

Table 7 evaluates the economic feasibility of deploying HCF across different segments of the Indian telecommunications market. It shows that HCF is highly viable in High-Frequency Trading (HFT) due to the significant financial benefits of ultra-low latency. It has moderate viability in Hyperscaler Data Center Interconnect (DCI) and AI/ML clusters, where performance gains justify higher costs. However, its use in mobile backhaul is currently not viable due to cost constraints and lower sensitivity to latency improvements. This segmentation highlights that HCF adoption will initially be limited to niche, high-performance use cases.

Table 8: Global HCF Adoption Landscape by Sector. This highlights how different industries are currently adopting HCF, mapping out the target markets.

Adopter Category	Key Players	Primary Use Case	Deployment Stage	Justification
High-Frequency Trading	euNetworks, Jump Trading, Anova, McKay Brothers, BSO, DRW	Ultra-low latency exchange connectivity	Full Production (3+ years)	Microsecond advantages generate millions in revenue
Hyperscale Cloud	Microsoft Azure, AWS; Google and Meta evaluating	DCI for AI/ML workloads; AZ interconnect	Production (two hyperscalers live)	Competitive advantage + geographic flexibility + AI workload acceleration
Telecom Operators	China Mobile, China Telecom, BT, Comcast	Metro/DCI, 5G fronthaul	Trial / Early Production	Future-proofing; evaluating technical feasibility
Data Center Operators	Digital Realty/Interxion, lyntia, Equinix (evaluating)	Low-latency interconnects	Trial / Limited Deployment	Premium latency services for HFT/cloud clients
Defense / Government	DARPA, Honeywell	Fiber optic gyroscopes, secure comms	R&D / Advanced Prototyping	20x Faraday effect reduction; intrusion detection
Enterprise / General SP	Not yet adopted	N/A	Not started	Cost prohibitive; awaiting standardization

Table 8 provides a comprehensive overview of how different industries are adopting HCF technology globally. High-frequency trading firms such as euNetworks and Jump Trading have already implemented HCF in full production to achieve microsecond-level latency advantages. Hyperscale cloud providers like Microsoft Azure and AWS are deploying HCF for data center interconnects to support AI workloads. Telecom operators are in trial or early production stages, while data center operators are exploring HCF for premium services. Defense and government sectors are using HCF in advanced R&D applications due to its unique physical properties. However, general enterprise adoption has not yet begun due to cost and standardization challenges.

Table 9: Key Players in the HCF Ecosystem A comprehensive look at the vendor and manufacturing landscape supporting the global HCF supply chain.

Company	Type	HCF Technology	Strategy	Status
Microsoft / Lumenisity	Vertically Integrated User	DNANF (Double-Nested ARF)	Internal Azure deployment; vertical supply chain with Corning & Heraeus	Production (1,280+ km deployed; 15,000 km target by late 2026)
AWS (Amazon)	Hyperscaler User	Proprietary HCF design	Long-distance AZ interconnect	Production (~10 DCs connected; scaling aggressively)
Lightera (formerly OFS)	Merchant Supplier	Photonic Bandgap (AccuCore)	Turn-key solution with factory termination	Commercial product; multiple deployments
Relativity Networks	Startup / Merchant Supplier	Anti-Resonant HCF	DCI market; co-manufacturing with Prysmian	Production (deployed with US hyperscalers)
Prysmian Group	Cable Manufacturer	AR-HCF (via Relativity)	Mass production at Eindhoven facility	Manufacturing partnership active
YOFC	Fiber Manufacturer	AR-HCF (Proprietary)	Record performance (0.05 dB/km); China & exports	Production-grade capability
Corning	Incumbent Fiber Giant	DNANF	HCF production under Microsoft IP	Manufacturing (production for Microsoft)
Heraeus Covantics	Quartz & Silica Specialist	DNANF	HCF production at US and European sites	Manufacturing (production for Microsoft)
Linfiber Technology	Chinese Manufacturer	AR-HCF	Pluggable connectors; China Mobile partner	Production-grade (deployed in Shenzhen)
Hengtong Optic-Electric	Chinese Fiber Manufacturer	AR-HCF	Expanding into HCF production	R&D / Early production
VIAVI Solutions	Test & Measurement	N/A (Testing equipment)	Industry-first HCF bidirectional testing solution	Commercial product (Jan 2026)
Furukawa Electric	Equipment Manufacturer	N/A (Splicer manufacturer)	Specialized HCF splicers with Ring-of-Fire tech	Commercial equipment available

Table 9 outlines the global ecosystem of companies involved in the development, manufacturing, and deployment of HCF technology. Major hyperscalers such as Microsoft and AWS are leading adoption through vertically integrated strategies. Fiber manufacturers like YOFC, Corning, and Prysmian are driving innovation in production, while startups such as Relativity Networks are focusing on commercialization. Supporting companies like VIAVI and Furukawa Electric provide testing and splicing solutions. This ecosystem demonstrates a rapidly evolving supply chain with increasing collaboration between technology developers, manufacturers, and end-users.

Table 10: HCF Operational Maturity Timeline by Application Domain A projected roadmap for when HCF will become commercially viable across different networking layers.

Timeframe	Milestone	Target Application	Key Enablers
2024-2026	Multi-hyperscaler production maturity	HFT, Hyperscale DCI (Microsoft, AWS)	Microsoft 15,000 km target; AWS ~10 DC deployment; VIAVI test platform
2026-2028	Multi-vendor DCI evaluation + expansion	Premium DCI for cloud/AI operators	Multiple production supply chains; first ITU-T study groups; standardized testing
2028-2030	Standardized DCI deployment	Broader DCI; tier-1 service provider trials	ITU-T recommendations; cost reduction to \$1-2/m; standardized splicing
2030-2033	Service provider metro adoption	Metro/regional latency-sensitive routes	Multi-vendor interoperability; trained workforce; cost approaching \$0.50/m
2033+	Mainstream deployment	Long-haul, submarine; general metro	Full cost parity, mature supply chain, complete standardization

Table 10 presents a projected timeline for the commercialization and adoption of HCF across different networking domains. Between 2024 and 2026, HCF is expected to achieve maturity in hyperscaler and high-frequency trading applications. From 2026 to 2028, multi-vendor evaluations and early standardization efforts will expand its use in premium data center interconnects. By 2028–2030, standardized deployments and cost reductions will enable broader adoption by service providers. Between 2030 and 2033, HCF is expected to enter metro networks, followed by mainstream deployment in long-haul and submarine networks after 2033. This roadmap highlights a gradual transition from niche applications to widespread adoption as costs decrease and technology matures.

II LITERATURE REVIEW

Chen et al. (2025) proposed a frequency-domain method to accurately measure group delay and chromatic dispersion in hollow-core fibers, even in the presence of higher-order modes [19].

Sun et al. (2023) designed low-loss hollow-core anti-resonant fibers operating at the 2 μm band, achieving ultra-low attenuation and high mode extinction ratios [20].

Szwaj et al. (2024) demonstrated that double-clad anti-resonant hollow-core fibers significantly improve multiphoton imaging performance with low loss, minimal nonlinearity, and higher signal-to-noise ratio compared to solid-core fibers [21].

Yu et al. (2023) reviewed hollow-core photonic crystal fibers for gas sensing applications, highlighting their ability to overcome limitations of conventional solid fibers [22].

Qin et al. (2025) developed a hybrid hollow-core fiber structure achieving extremely low confinement loss and excellent single-mode performance for optical communication systems [23].

Melli et al. (2025) proposed an optimized polarization-maintaining hollow-core fiber design using multi-objective techniques, achieving high birefringence with reduced confinement loss [24].

Yang et al. (2025) analyzed the effect of surface roughness on propagation loss in hollow-core fibers, concluding that loss is influenced by spectral properties rather than roughness magnitude alone [25].

Zong et al. (2025) designed a few-mode hollow-core anti-resonant fiber with high modal purity and low confinement loss, suitable for advanced communication systems [26].

Xiao et al. (2024) developed a hollow-core fiber-based sensor capable of simultaneously measuring temperature and strain with high sensitivity [27].

Geng et al. (2024) proposed an all-fiber remote gas sensing system using hollow-core fiber, achieving faster response time and high detection sensitivity [28].

Li et al. (2025) introduced a hybrid hollow-core fiber structure with improved ultra-low loss and enhanced single-mode transmission characteristics [29].

Table 11: Literature Review of Hollow Core Fiber (HCF) Technologies and Applications

Author & Year	**Objective**	**Methodology / Technique**	**Domain / Application**	**Key Findings / Results**
Chen et al. (2025)	Measure group delay and chromatic dispersion in HCF	Frequency domain measurement approach	Optical fiber characterization	Accurate dispersion measurement even with higher-order modes
Sun et al. (2023)	Design low-loss HCF at 2 µm band	HC-ARF design analysis	Optical communication	Achieved ultra-low loss (~0.040–0.042 dB/km) with high mode extinction
Szwaj et al. (2024)	Improve multiphoton imaging using HCF	Double-clad ARF vs SCF comparison	Medical imaging (endoscopy)	HCF shows low loss, no nonlinearity, and 3× better SNR
Yu et al. (2023)	Review gas sensing using HC-PCF	Review of sensing mechanisms	Gas sensing	HCF overcomes limitations of solid fibers

Qin et al. (2025)	Design ultra-low loss HCF structure	Hybrid nested fiber design	Optical communication	Achieved extremely low loss (0.00033 dB/km)
Melli et al. (2025)	Optimize birefringence vs loss	Pareto optimization	Polarization-maintaining fiber	Achieved high birefringence with low confinement loss
Yang et al. (2025)	Study loss due to surface roughness	Coupled-mode theory model	Fiber design analysis	Loss depends on spectral roughness, not RMS value
Zong et al. (2025)	Design few-mode HCF	Nested anti-resonant structure	Optical communication	High mode purity and low loss achieved
Xiao et al. (2024)	Develop HCF-based sensor	Nested ARF sensor design	Temperature & strain sensing	High sensitivity (3.36 nm/°C) achieved
Geng et al. (2024)	Develop remote gas sensing system	AR-HCF + MH-ECF integration	Environmental monitoring	30× faster response time; high sensitivity
Li et al. (2025)	Optimize hybrid HCF structure	Elliptical + semi-circular design	Optical communication	Improved single-mode and ultra-low loss performance

III CONCLUSION

Hollow Core Fiber is the most profound breakthrough in optical transmission media in forty years, shattering the latency and attenuation limits of solid glass. While deployments by cloud giants like Microsoft (using Lumenisity technology) and foreign operators prove its operational viability, the 50-100x cost premium, complex splicing requirements, and high terrestrial disruption environment mean HCF is not yet ready for mass rollout in India's general broadband network. The approach should be proactive but pragmatic, immediately investing in lab evaluations and target premium enterprise routes while awaiting global manufacturing scale-up to drive costs down for broader regional deployment by the early 2030s.Hollow Core Fiber (HCF) technology represents a significant advancement in optical communication, offering substantial improvements over conventional Single Mode Fiber (SMF) in terms of latency, attenuation, bandwidth, and nonlinear performance. By enabling light to propagate through an air-filled core rather than solid glass, HCF achieves near-vacuum light speed transmission, resulting in ultra-low latency and reduced signal distortion. The comparative analysis demonstrates that HCF outperforms SMF across several critical parameters, including chromatic dispersion, thermal stability, and power handling capacity, making it highly suitable for next-generation high-speed communication systems.

The literature review further highlights rapid advancements in HCF design, including anti-resonant and hybrid fiber structures that achieve ultra-low loss and improved single-mode performance. Researchers have successfully demonstrated the application of HCF in diverse domains such as optical communication, sensing, medical imaging, and environmental monitoring. These studies confirm that HCF has the potential to revolutionize high-capacity data transmission and enable emerging technologies such as 5G/6G networks, hyperscale data centers, and high-frequency trading systems.

However, despite its technical advantages, HCF faces several challenges that limit its widespread adoption. High production costs, complex splicing requirements, limited standardization, and lower operational maturity compared to SMF remain key barriers. Additionally, issues related to scalability, technician expertise, and infrastructure compatibility must be addressed before large-scale deployment can be achieved.

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