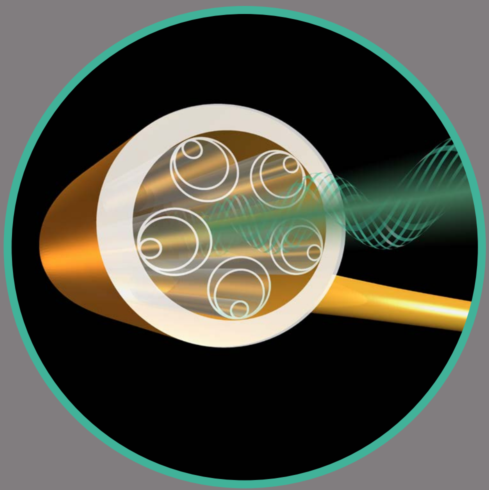
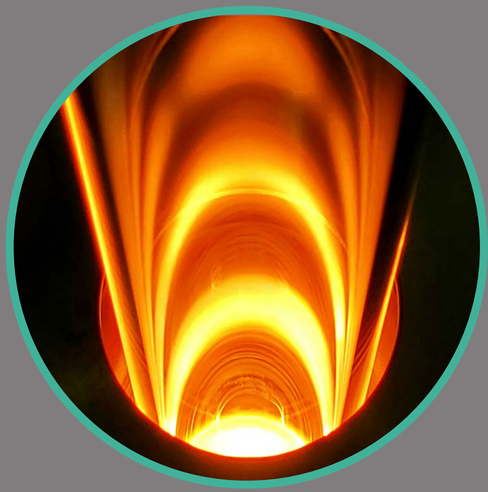
LUMENISITY®

Connect. Light. *Faster.*





A Lumenisity White Paper: CoreSmart® Hollowcore Cable Solutions

www.lumenisity.com

Introduction to NANF® hollowcore fibre

Lumenisity's CoreSmart® hollowcore optical interconnect solutions are unique. Our patented, record breaking* and award-winning[1] NANF® (nested anti-resonant nodeless fibre) is igniting interest across the optical communications industry in a new hollowcore technology space. Since our formation in 2017 as a spin-out from the University of Southampton, our goal has been to create and develop innovative hollowcore cable solutions that redefine the capabilities of next generation optical networks. From the very first hollowcore installation carrying production traffic in 2018, we have focused on providing the world's best performing hollowcore cable solutions that are robust and easy to install. However, this has been achieved by retaining compatibility with conventional single mode fibre (SMF), on which the optical telecom ecosystem is generally based.

Our hollowcore solutions continue to use fibre jointing and monitoring techniques that utilise common industry installation practices. They can also be field spliced using commercially available splicing equipment, thereby overcoming barriers that have previously prevented broader adoption of hollowcore in longer link length optical networks.

Numerous independent studies have demonstrated that our technology also supports leading edge multi-channel 400/800Gb/s data transmission using commercially available equipment. It therefore vastly surpasses the capabilities of other hollowcore cable solutions. Furthermore, near-term improvements in attenuation will support long-haul applications over distances reaching thousands of kilometres with fewer amplifiers. In this white paper we will share the results of several independent testbed studies, which demonstrate successful reach over such distances using amplified recirculating loops.

This technology has enormous potential to address the fundamental limitations of conventional fibre networks that face challenges of high bandwidth demand whilst understanding how to support the needs of lower latency applications.

This white paper explains how Lumenisity's NANF technology is uniquely different from other types of hollowcore fibre, and how its higher transmission capacity-x-reach potential, combined with ultra-low latency, could revolutionise optical network design. For example, in applications such as high-frequency trading (HFT), hollowcore technology can be deployed more easily and over much longer link lengths, thereby providing far greater latency reduction than other optical fibre types. Furthermore, by redefining the time-distance latency Availability Zone Envelope (AZE) applicable to Data Centres (DC) and Edge computing, NANF-based hollowcore cabling could expand the geographic coverage area of existing DC sites and enable greater flexibility in design, size and DC infrastructure placement, providing vast cost savings for operators.

**NANF-based technologies have broken several records, including lowest loss, longest reach and highest transmission capacity of any hollowcore fibre cables.*

What is NANF hollowcore fibre?

NANF is an innovative state-of-the-art hollowcore optical fibre technology. The concept was first developed by the University of Southampton and led to the formation of Lumenisity in 2017 to further progress this technology and develop commercial NANF-based cabled fibre solutions. The term 'NANF' describes the structure of non-contacting, nested glass capillary tubes that are fused to the inside circumference of an outer glass tube, which makes the fibre cladding. This structure forms a predominantly single mode waveguide. The light signals propagate through air along the central axis, with very little coupling loss over a broad range of operable wavelengths and an extremely high extinction of any higher order modes. Light travelling through air rather than glass provides several distinct advantages, such as: lower latency, higher power handling, and virtually no non-linear signal impairment, which is beneficial for high bit-rate, high capacity multi-channel telecommunications applications. The glass cladding has a protective coating that is vibrantly colour coded for use inside multi-fibre strand cables, making them readily identifiable and discernible when splicing in the field.

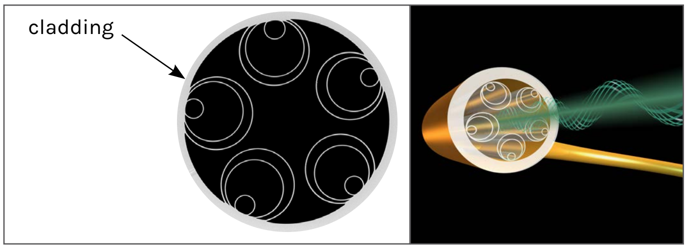


Figure 1: Cross-section the NANF structure and software model to illustrate light propagation and signal loss

What are the advantages of hollowcore fibre?

Light travelling through air in a NANF hollowcore fibre travels 1.5x faster than in conventional fibre types that are made entirely of glass. This provides latency savings of 1.5μs/km or 3μs/km RTT (round trip time).

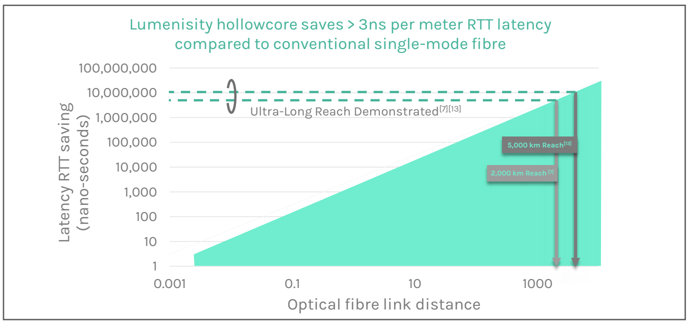


Figure 2: Latency of hollowcore compared to glass-core fibre

The latency savings are achievable with NANF over distances that surpass those of any other hollowcore optical fibre solution, due to its lower attenuation and ability to be field fusion spliced. This enables NANF hollowcore cables to be installed over longer route lengths, for example inside ducts, with multiple segments of jointed cable.

NANFs compatibility with, and ease of jointing to, solid SMFs using Lumenisity's technology also means that it can be readily used with erbium-doped fibre amplifiers (EDFAs) to increase system reach. EDFAs can be used at a transmitter to boost signal power or as a pre-amplifier at the receiver to increase sensitivity. Additionally, they can be deployed as in-line amplifiers, in multiple spans along longer routes, to further extend transmission reach to thousands of kilometres. These advantages, unique to Lumenisity's NANF hollowcore solutions, have attracted the attention of network operators that face capacity or latency challenges in their optical network infrastructure.

There are multiple potential use-cases for lower latency in optical networks. In the financial industry, High Frequency Traders (HFTs) require low latency, high transaction rates and rapid response times to fluctuations in stock trading. In back-haul optical networks, DC interconnects (DCI), Cloud and Edge Computing functions require a combination of high-speed, high-data capacity and fast data processing functions. These are increasingly challenged by geographic coverage and a rise in time-sensitive applications such as data replication and backup as well as virtual and augmented reality.

The LOWEST Latency – the NEW trading edge

Lowest latency underpins financial transactional speed-success for HFTs. Sub-nanosecond (10^{-9}) time savings offer a competitive transaction advantage. Hollowcore TradeSmart® fibre cables can save >1.5ns per metre deployment length over conventional glass-core optical fibres. They also present a reliable alternative to long-range microwave point-to-point links that are susceptible to line-of-sight impairments due to adverse weather, electromagnetic interference or where placement of radio masts is restricted or prohibited. Lumenisity has deployed Hollowcore TradeSmart cables that provide a trading edge for HFT applications since 2018. These have been installed in multi-segment fusion splice jointed cable lengths in Europe and the US. They are designed to withstand exposure to seasonal weather extremes both above ground and in buried ducting that is prone to flooding. Lumenisity's Hollowcore TradeSmart cables have proved reliable with error-free transmission, superior to other line of sight air-radio-based links.

Lumenisity has also developed short reach Hollowcore TradeSmart interconnects with direct pluggable interfaces (DPI). These are pre-terminated hollowcore cables providing direct single mode compatible interface connectivity for inside the DC or Exchange. They are for rack-to-rack or patch-panel connections to a trading engine or switch, using industry standard types of optical connector (e.g. LC or SC) that are compatible with small form factor (SFP, SFP+, QSFP, QSFP DD, OSFP etc.) optical transceiver ports. This offers HFTs a direct pluggable ultra-low latency hollowcore patch cord solution that can be customised in short lengths, e.g. 1 metre or less, and is part of a number of indoor/outdoor interconnect cable solutions that can complement latency savings over longer link lengths spanning 10s of kilometres. Lumenisity's Hollowcore TradeSmart solutions offer ultra-low latency opportunities for HFTs and Carriers seeking ways to reduce latency in their systems.

Why is the capability of optical fibre so important in telecom?

Optical cables form the backbone of increasingly diverse digital telecommunication networks, transforming the ways in which we interact and communicate with each other. However, demand for data services continues to rise. In 2019, internet traffic was increasing exponentially at over 30% annually[2] and is expected to double by 2022[3]. For every bit of data sent or received between a Data Centre (DC) and a user, five bits of data are transmitted within a DC and between DCs[4].

Network infrastructure interconnecting DCs to other DCs and users is increasingly challenged by the growing number of users and connected devices. In 2025, the amount of internet users is expected to have risen from 3.8 billion in 2019 to 5 billion. In that same timeframe, the number of connected internet of things (IoT) devices will have doubled to over 25 billion[5].

Remote working, distance learning, autonomous control and broader use of rich high-definition media is driving uptake of more complex applications, such as augmented and virtual reality. Increasingly, these and future applications demand not only high data-capacity but also low or lower latency. This means a low or reduced time lapse between sending and receiving data to and from a DC location and the time taken to process the data, which is necessary for the application to function properly. Latency can be attributed to the speed of the data transmission (bit-rate), the speed of the transmission signal (the speed of light travelling in a fibre) and the time taken to access or process large and growing volumes of data. Support for some applications can be limited by AZE, which is the maximum interconnected link (time/distance) between DC-DC or DC-user that can be tolerated for synchronous replication, for example.

Low Latency – advantage and cost saving for DC geographic expansion

DCs are expensive to build and operate, consuming large amounts of energy to power electronics and for cooling (10~100s of Megawatts). This accounts for ~1% of worldwide energy consumption and continues to rise despite efforts to improve efficiency[3].

Virtualization and Cloud Computing based service provisions mean that one or more DCs mirror or share the function of processing, moving and storage of vast volumes of data at high speed between DC sites and users. This is known as synchronous replication and is a key Quality of Service requirement. The proximity of DCs to their consumer-base and that of neighbouring DC sites, for shared service or back-up function, is being increasingly limited by the latency of incumbent glass fibre routing.

NANF-based CoreSmart hollowcore cables enable 31% latency saving over conventional SMF and support multi-terabit data speeds over single fibre strands. Light travelling in conventional glass optical fibres experience a round-trip-time (RTT) of one millisecond for every 100km of separation compared to 670 microseconds in hollowcore fibre.

CoreSmart cabled NANF hollowcore fibres were the first types of hollowcore fibre capable of supporting multi-terabit capacity using dense wavelength division multiplex (DWDM) channels operating at bit-rates of 10, 400 (400ZR) and 800Gb/s using commercially available transmission equipment[5][6][7]. Therefore, lower latency CoreSmart cables can extend a given AZE distance DC-DC separation by 1.5x or expand geographic AZE coverage by 2.25x. This is a game changing technology for DC owners and operators.

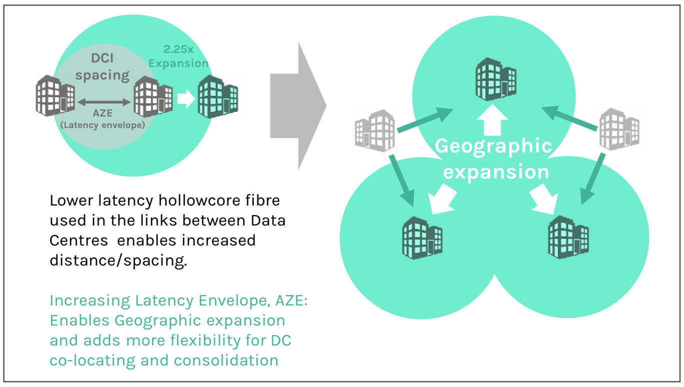


Figure 3: Lower latency DCI offers cost saving options enabled by DC Geographic expansion

Lumenisity's new generation of low latency, high data capacity hollowcore fibre cable can offer significant cost savings for DC operators and tenants looking to rationalise DC costs by boosting AZE coverage through greater separation, consolidation or co-location.

DC placement in lower cost real-estate areas that are further away from major city centres can contribute to multi-million-pound savings in build costs. At the same time, they can increase access to cheaper and greener sources of renewable energy such as solar, wind and geothermal, aiding additional cost savings with further sustainable reductions in CO_2.

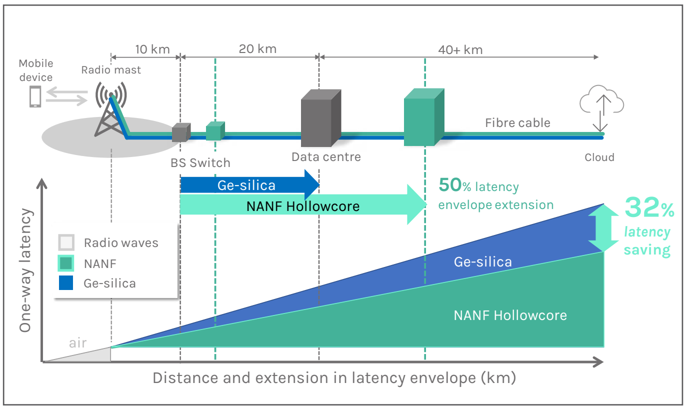


Figure 4: Signal path latency in cellular radio-fibre networks

The latest generation of cellular networks are expected to support >80% of all mobile traffic. This aids the rise in data consumption in HD & 3D video, Machine-Machine communication and online gaming which is expected to quadruple by 2022[8]. A challenge for mobile operators is the rollout of 5G and enabling their networks to function with 10~100x faster upload/download speeds, 100x more connected devices per unit area and latency of 1ms, 100x lower than 4G/LTE[9]. Figure 4 demonstrates how hollowcore fibre, used in the back-haul between Cloud and DCI and in parts of the front-haul radio links, could help reduce latency for time-critical applications. This could assist with Switch and DC site placement, coverage and consolation to help off-set costs of 5G rollout.

Optical Transmission Properties

Light propagation in air has the potential to reduce attenuation below that of solid glass fibres. Interactions between light signals and the glass gives rise to optical scattering and absorption mechanisms that result in attenuation. Pure silica core (PSC) fibre designs used in long distance applications help to reduce attenuation of more widely deployed germanium (Ge) doped core designs that are used in Metro, Edge and FTTx networks. The slightly lower refractive index of PSC fibre reduces Rayleigh backscattering and light absorption helping to lower attenuation below 0.16 dB/km for state-of- the-art designs at 1550 nm. In contrast, conventional Ge-doped single mode has an attenuation of approximately 0.20 dB/km. Earlier generations of hollowcore technology such as PBGF have struggled to achieve better than 10dB/km and were not field deployable in cabled networks, owing to their more complex waveguiding lattice structures that were very difficult to joint and manage higher order modes. Recent advances in NANF hollowcore technology have demonstrated far greater improvements in attenuation, typically 10x or greater reduction in the C and L band. NANF fibre can also be operated in the O-band and is capable of supporting similar short reach campus or rack-to-rack link lengths that currently use SMF e.g. up to 2 kms.

Table 1 compares some of the optical properties and the main practical transmission considerations for NANF hollowcore, PBGF and conventional SMF.

	Fibre Technology Type		
	NANF	**PBGF**	**SMF (G.652)**
Transmission Medium	(Hollowcore) Air	(Hollowcore) Air	Solid glass
Cladding Material	Silica	Silica	Silica
Fibre Spliceable	✓	x	✓
Field Fusion Spliceable	✓	x	✓
Compatibility with SMF	✓	x	✓
O-Band ≥1260 - 1330nm	✓	x	✓
C-Band 1530 - 1565nm	✓ uninterrupted DWDM window > 200nm*	partial limited to 15nm	✓ conventionally 95nm of spectrum
L-Band 1565 - 1625nm	✓ uninterrupted DWDM window > 200nm*	partial limited to <50nm total non-continous spectrum	✓ conventionally 95nm of spectrum

Table 1: Operating characteristics of hollowcore fibres

The publication of attenuation values of 0.28dB/km for NANF fibre that extend beyond the conventional C and L bands has sparked excitement for hollowcore fibres in the optical fibre industry[10]. Moreover, the characteristics of NANF in the C and L band suggest greater optical fidelity is possible due to a combination of favourable transmission characteristics that are advantageous for long distance and high data capacity: i) low attenuation, ii) lower non-linearity, iii) lower and flatter chromatic dispersion coefficient, iv) higher- power handling capability, and v) a broader operating spectrum. These can be utilised to greatly increase the capability of hollowcore fibre, and if the attenuation improves further as is planned, it could rival high-performing types of SMF in terms of capacity and reach.

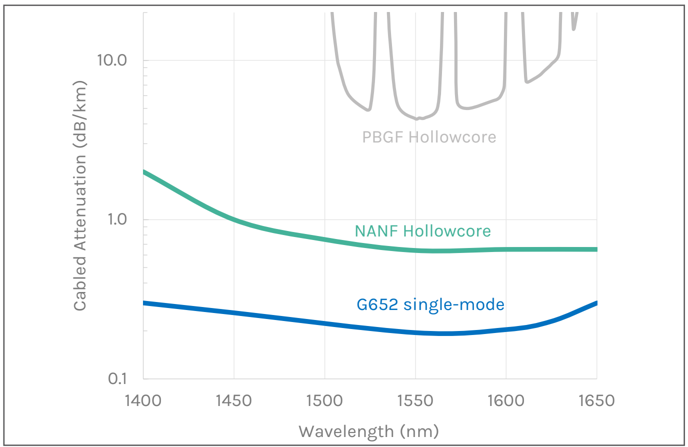


Figure 5: Comparison of spectral attenuation

Lumenisity is currently (2021) supplying CoreSmart cables with a field deployable attenuation coefficient of ~1dB/km (figure 5) and anticipates lower attenuation approaching SMF in the near term. Research results have been published that show the potential of NANF fibre with lower attenuation of 0.22dB/km, as already demonstrated by our R&D groups[12].

Alleviation of Non-linear signal impairments

Light guided within air does not experience non-linear effects that can penalise transmission with conventional fibres. In glass core fibres employed for long-distance and high data capacity, a careful design-balancing act is needed to create optical waveguides with higher levels of chromatic dispersion to help counteract the non-linear effects of light propagating through glass. Four-wave mixing (FWM), self-phase modulation (SFM) and cross-phase modulation (XPM) are sources of signal distortion that reduce optical-signal-to-noise-ratio (OSNR). These non-linear effects greatly penalise high bit-rate, multi-channel, dense wavelength division multiplexing (DWDM) systems operating over long distances. In these types of networks, XPM can be a significant penalty that imposes restrictions on total launch power, limiting total capacity and reach.

Backhaul routes operating at bit-rates ≥100Gb/s or higher use coherent transmission techniques. These are inherently more resilient to noise and distortion but are also heavily reliant upon electronic digital signal processing (DSP) to counteract accumulated dispersion of conventional fibre. Forward error correction (FEC) is sometimes required for very high capacity and long reach, which comes at the expense of additional latency, power consumption and cost. These can be limiting factors for networks, posing challenges for operators faced with growing demand and faster bit-rate capable networks with restricted spectrum. They require more spectrally efficient modulation formats based around 64-QAM or higher which are much less tolerant to noise and distortion, and thus total reach limited.

In contrast, the light propagating in NANF hollowcore fibre experiences virtually no backscatter or Kerr effects (non-linear behaviour). This allows higher optical flux density in the core with almost zero signal penalty and without the need for higher fibre dispersion designs to mitigate nonlinear effects. In fact, NANF fibre has a much lower chromatic dispersion coefficient that remains flat over an operating spectrum that is broader than the C and L bands combined.

The dispersion coefficient of NANF fibre is ~3 ps/nm km in the C and L band, which is approximately 5x lower than conventional G652 and G.654 SMFs used in long haul networks.

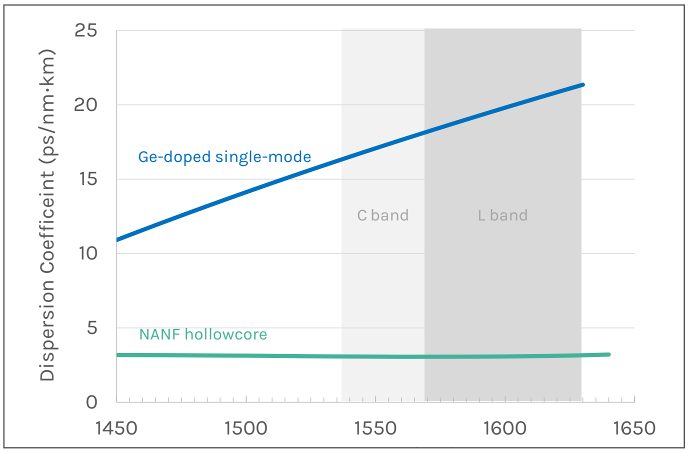


Figure 6: Comparison of chromatic dispersion (cabled fibre)

This advantage could help extend the uncompensated reach of direct-detection based transmission by up to 5 ~ 10x with bit-rates of 25Gb/s, 50Gb/s or higher, without the need for additional DSP to help further reduce latency for example in 5G and access network links.

The absence of nonlinear penalties could enable the use of higher order QAM-based modulation techniques, which are more spectrally efficient, to further increase data transmission speeds. NANF could boost capacity with potentially more channels, transmitted over extended uncompensated distances, by up to 5x that of PSC or Ge-doped fibre, using a broader spectrum, wider than current C and L band combined. In contrast, PBGF hollowcore for example, has a much smaller operating spectrum, which is segmented by the filtering effects of the lattice structure. PBGF typically has higher attenuation and dispersion coefficient that are characteristics of the lattice structure and vary greatly across the C band wavelength range. This makes PBGF-based fibres less well suited to multi-channel, multi-window operation and could limit lower bit-rate speeds.

Published Transmission Performance for CoreSmart hollowcore cables

To demonstrate the transmission performance of NANF hollowcore fibre based cable solutions, Lumenisity asked independent parties to test its CoreSmart hollowcore cables in various transmission testbeds, simulating real world data carrying capability with commercially available equipment. For this type of testing, Lumenisity produced test emulators, comprising of drum wound cable containing hollowcore fibre (spliced at each end of the cable). Patch panels were fitted with standard single mode pluggable connector interfaces using Lumenisity's hollowcore SMF Smart Adapters.

In one such study, Ciena's WaveLogic WL5n (400Gb/s ZR) and WL5e (800G 91.6Gbaud) transmission equipment was used to test a 20.5km hollowcore link, comprising of 2x 10km fibre-length emulators that were interconnected with G652 single mode, with a total loss of 19.9dB (including splices and connectors). Figure 7 shows the configuration that used an EDFA booster at the transmitter, with a launch power of +23.5dBm, connected via an optical isolator to the first emulator.

A second isolator was connected between the emulators to reduce optical back reflections at glass-air interfaces that might cause amplifiers to enter a safety mode and power down. This would not be required in the field and is a consequence of the experimental set up. A pre-amplifier was used to increase sensitivity at the receiver. In field deployed links, HCF-HCF fusion spliced cable joints eliminate the need for a second isolator. We also anticipate changes to amplifier firmware controls and use of automated link monitoring, utilising a service channel wavelength (e.g. 1650nm), could eliminate the need for an optical isolator when launching in to HCF. The results of the testing are summarised in table 2, with the links operating error-free in long term bit-error-rate testing (BERT) when supporting a total transmission capacity of 19.2Tb/s (400G-ZR) and 38.4Tb/s (800G).

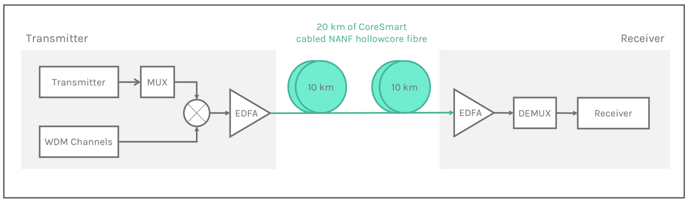


Figure 7: 20.5km point-to-point link demonstrating 19.2Tb/s & 38.4 Tb/s[7]

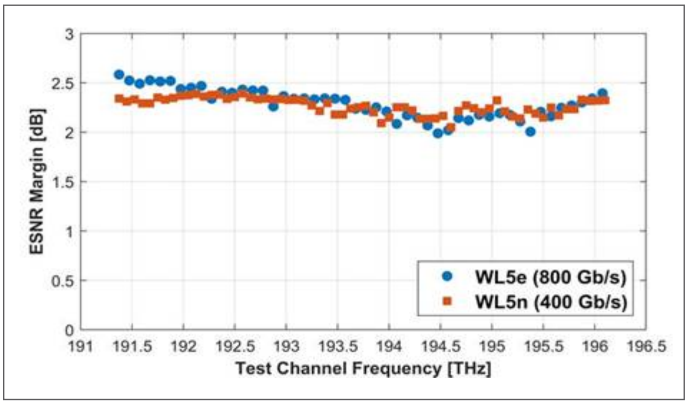


Figure 8: Plotted results showing ESNR vs Channel Frequency

	Bit-rate (Gb/s)	
	400 (WL5n/ZR 60Gbaud)	800 (WL5e 91.6Gbaud)
No. of Channels & Spacing	64Ch - 75GHz	48Ch - 100GHz
Total Capacity (Tb/s)	19.2	38.4
Cabled Distance (km)	2 x 10	2 x 10
Excess SNR Margin (dB)	2 ~ 2.5	2 ~ 2.5

Table 2: Transmission performance of 2 x 10km point-to-point link[7]

To demonstrate performance over longer distances, a recirculating loop was formed using the same hollowcore cable emulators. This created a total transmission distance of over 2000km to simulate a long-haul network using in-line EDFA amplifiers (see figure 9).

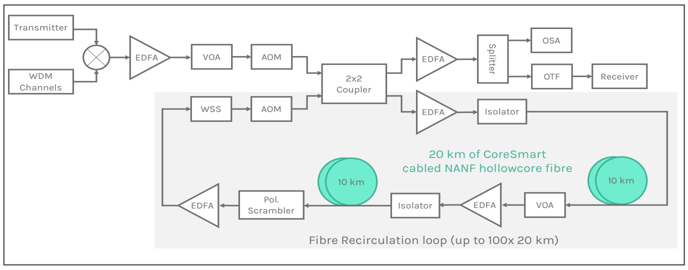


Figure 9: A recirculating loop was used to demonstrate 400Gb/s over more than 2,000 km of cabled NANF hollowcore fibre

In a series of experiments, transmission performance was demonstrated with 45 DWDM channels with data rates of 400Gb/s and 800Gb/s. These experiments show that beyond the current attenuation level of the link, our hollowcore technology is intrinsically capable of supporting extensive long-haul distance transmission. Up to 45 DWDM channels, carrying a total capacity of 18Tb/s, was transmitted over a total link distance of between 1128km and 2007km.

In other work press released during OFC 2021[11], thought to be the first demonstration of 400ZR DWDM transmission over field deployable hollowcore fibre cable, BT demonstrated error-free transmission of 38 DWDM channels at 400Gb/s in the C-band over 10km of cabled fibre (15.2 Tb/s).

These transmission studies helped to show what Lumenisity system models had predicted. That the diminished non-linearity of single-mode propagation inside the NANF air waveguide, in combination with much lower and flatter dispersion, has no fundamental limitations, beyond the current attenuation (of ~ 1dB/km or less of current generation of fibre), with current state-of-the-art transmission equipment. Furthermore, by continuing along its path of delivering lower attenuation in hollowcore cable, the possibilities to further optimise transmission protocols could be boosted by leveraging the higher power handling and broader operating spectrum to increase the total bandwidth-reach. This means that this type of hollowcore technology and evolution in transmission equipment could deliver even greater capacity in long-haul networks and subsea systems as the attenuation coefficient is reduced.

Ruggedized CoreSmart cables – Field deployable for indoor and harsh outdoor environments

Lumenisity's NANF hollowcore fibre cables can be handled and installed in a similar fashion to conventional optical cable types. The protective fibre coating can be mechanically stripped using commonly available tools. Hollowcore glass can be cleaved and fusion spliced using commercially available cleavers and fusion splicers. Lumenisity has developed CoreSmart cables that are optimised for indoor applications and work with existing racking and shelving equipment commonly found inside DCs and other indoor networking spaces. Lumenisity has also developed outdoor cables that have been operating in external duct-install applications for over four years, and is continuing to develop a portfolio of cable solutions for broader applications and installation methods.

Installation and Training

Lumenisity has developed fusion splicing programs for fibre splicing equipment that enable its hollowcore fibre cables to be field spliced and terminated to SMF-based interfaces, components and equipment, such as pigtails. This allows NANF hollowcore fibre to be connected and used with SMF and associated components and equipment, including splitters, multiplexers and amplifiers. Lumenisity provides a training program for cable installers on how best to install, joint and splice its hollowcore fibre cables designed for indoor and challenging outdoor terrain. Please email hollowcore@lumenisity.com for more details.

Figure 10: Mechanically strippable fibre coating

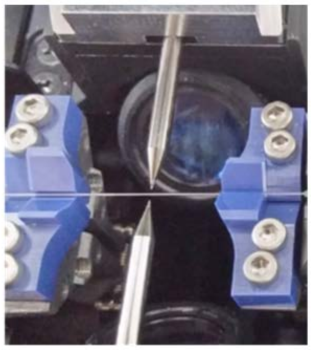


Figure 11: Field fusion splice capable using commercially available equipment

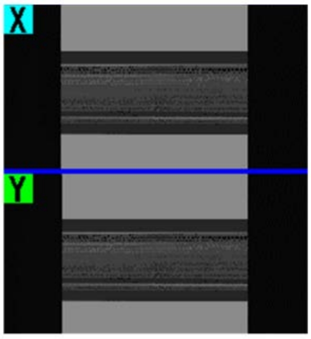


Figure 12: A splice machine screen image of fused NANF hollowcore fibre

Figure 13: Cable being deployed in in existing duct infrastructure in a harsh environment

Key advantages of NANF hollowcore technology

- A disruptive optical fibre technology that can significantly reduce latency between DCs and 10s~100s millions in cost savings by DC geographic expansion
- 100% backwards compatibility with conventional SMF
- Operable in the O, C & L band with 200nm of continuous spectrum
- The LOWEST attenuation of any hollowcore fibre
- 1000x lower non-linear coefficient than SMF
- Long-distance field deployable, can be spliced in the field and be a complementary hybrid solution with SMFs

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