The Prospects of Hollowcore Fibres with Lower Attenuation Than Single-Mode Fibre

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Abstract *Nested Anti-Resonant Nodeless Fibre (NANF®) technology is achieving record attenuation values for hollowcore, near parity with single-mode fibre. We report the development of hollowcore capable of realising latency saving far beyond other cable types and the potential to redefine the capabilities of future optical networks. ©2022 The Author(s)*

Introduction

Rapid progress has been made in the development and performance of a unique type of hollowcore optical fibre, Nested Anti-Resonant Nodeless Fibre (NANF®). Cabled NANF is now being deployed in longer reach telecom applications than any previous type of hollowcore fibre cable technology.

We explore distinct advantages of NANF technology and its potential in CoreSmart® optical cables, to exploit lower latency and other transmission benefits, in metro-DCI link distances and beyond, in support of cloud computing, on-line gaming, 5G wireless and other future applications. In addition, we investigate how reductions in optical attenuation in combination with higher power handling, lower nonlinearity and dispersion and broader operating spectrum, could pave the way for wider use of hollowcore fibre (HCF) in more capable next generation optical backbones, boosting the geographic coverage of critical infrastructure such as largescale data centres (DCs).

Progress in Hollowcore

In the last five years the work to develop NANF has seen significant improvement in attenuation and a step change in transmission capability.

Early types of HCF had higher attenuation and more complex core designs that lead to compromises in optical performance, or their practical use cases were limited to short distance interconnects or high optical power (non-telecom) applications.

Yet, in a similar fashion to how early generations of solid-glass multimode gave way to development of single-mode fibre (SMF), with vastly better modal dispersion and attenuation, NANF has followed a similar path, with its unique advantages over earlier HCF concepts, such as photonic crystal and photonic band-gap fibres. For example, NANF is easier to splice and has a broader operating spectrum (C and L band). Both are fundamentally necessary for telecom reach applications. Fig. 1 shows how the design of NANF has evolved, enabling a step change in lower attenuation vs other HCFs developed by the ORC and compared to G652 SMF.

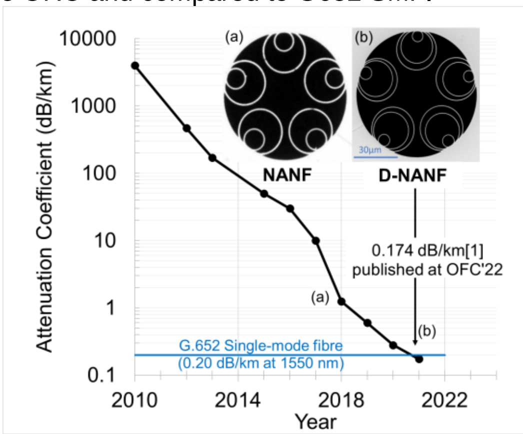

Fig. 1: Progress of HCF attenuation compared to SMF.

Lower Latency

HCFs are perhaps best known for their near-vacuum light speed advantage over solid glass fibres. With a group index of 1.003, light propagation is 1.5x faster enabling 1.5 μsec latency saving per kilometre or 3 μsec/km round trip time (RTT). Furthermore, HCF exhibits about 10x or better latency-temperature stability than solid silica fibres[1,2] that could be beneficial in applications where timing is critical, such as clock distribution for all optical switching.

Use cases of latency-saving HCF cables to date have included significant decreases in transaction times for high frequency trading. Here, CoreSmart hollowcore cables have proven reliable when exposed to harsh outdoor weather conditions and aerial environments.

Cable Link Length Latency Study

To verify real-world achievable latency savings over longer distances enabled by lower attenuation NANF, a network link was formed by jointing several multi-fibre cables in series. Six drum lengths (2~3 km) of hybrid CoreSmart cables (containing both HCF and SMF fibres), were measured to study latency before they were field deployed in underground ducting and used to interconnect between two DCs.

The CoreSmart cables used were non-metallic and constructed using conventional methods of manufacture: multi-fibre strands contained inside multiple, gel-filled thermoplastic loose-tubes, stranded around a (dry fully-water blocked core) glass reinforced plastic central element and polymeric outer sheath that was suitable for indoor and outdoor installation.

Segregation of HCF and SMF in differently coloured multi-fibre tubes made it possible to loop-back-splice extra neighbouring fibres from within the same tubes to extend the optical path length beyond the 14 km concatenated length of the six cables. This gave a reasonably close match in the end-to-end path lengths between the HCF and SMF for latency comparisons.

A low loss bidirectional mode-adapter, developed by Lumenisity® is used to interface between HCF and SMF at the termination ends of the HCF cables. This allows conventional SMF-based interconnects and existing transmission equipment to be used. Hybrid network links can also be formed by mixing both HCF and SMF in the same network signal paths.

Fig. 2 shows how the equipment and cabled fibres were connected to replicate a metro-DCI wavelength division multiplexed (WDM) network, operating over two link distances; #1 = 27.9 km and #2: = 30 km of both HCF SMF using loop-back splices.

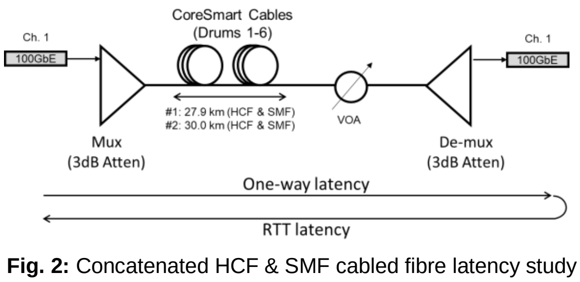

Fig. 2: Concatenated HCF & SMF cabled fibre latency study for Metro-DCI links.

200 Gb/s transponders were used to simulate live traffic transmission, latency and bit-error-rate testing, performed over 12 channel wavelengths in the C-band (1530~1565 nm). The average cabled attenuation was <1.0 dB/km for HCF and ~0.2 dB/km for SMF, respectively. Two 3 dB optical attenuators were used at either end of the link to replicate the insertion loss of WDM mux/de-mux. A variable optical attenuator (VOA) was used to verify error-free operation in longer duration soak-test experiments. The one-way latency of the transponders (connected back-to-back) was 5.9 μsec and the measured latency of the HCF and SMF cabled link lengths of 27.9 km and 30.0 km link lengths, is shown in Tab. 1.

Tab. 1: Link length latency(μsec).

Fibre Link #	Link Length (m)	One-way Latency	Latency Saving	RTT Saving
HCF (#1)	27,918	93.40	43.49	86.98
SMF (#1)	27,918	136.89		
HCF (#2)	30,066	100.59	46.83	93.66
SMF (#2)	30,066	147.42		

The NANF paths demonstrated >31% lower latency over SMF. Over 30 km of cabled NANF a latency saving of > 90 μsec was achieved compared to SMF and there was no difference in the bit-error rate performance (no errors). Testing with hybrid fibre links over 44 kms with (14 kms HCF + 30 kms SMF) was also successfully demonstrated.

Improvements in Attenuation

The pursuit of lower attenuation in HCF from ~5 dB/km about five years ago to <1 dB/km (C + L band) lead to the first demonstration of WDM 400 Gb/s supported by field deployable NANF cables with a total system reach of over >1000 km[3]. More recently lower attenuation in NANF has been achieved by optimization of the fibre design. More specifically, this relates to the arrangement of the thin-wall glass tubes that form the nested anti-resonant elements inside the cladding of NANF, shown in Fig. 1. The inclusion of secondary nested tubes in the anti-resonator structures (b) vs (a) labelled "D-NANF" significantly increases the confinement of light propagating along the core. Early fibres drawn using this preform design have achieved a much-improved step change with lower attenuation[4].

Fig. 3 shows the spectral attenuation of an un-cabled 'D-NANF'. The attenuation of other solid-silica fibre types plotted alongside, serve as a comparison to prominent telecom industry markers: i) SMF-28e+ representative of G652 used in FTTx, access and metro, and ii) lower attenuation, cut-off shifted (G654) pure silica core fibre types that are used in ultra-long haul subsea[5,6].

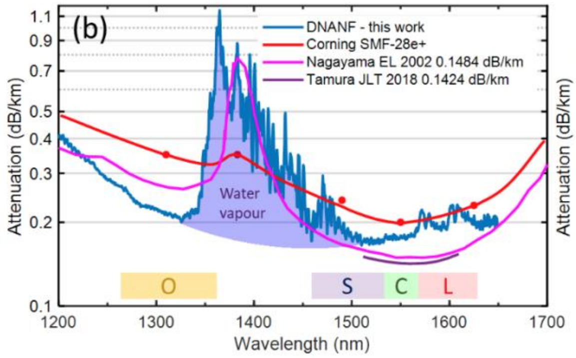

Fig.3: Spectral attenuation[4].

The 1310 nm measured attenuation of NANF of 0.22 dB/km is believed to be the lowest attenuation value published of any type of optical fibre. We also believe that at 1550 nm, attenuation of 0.174 dB/km is arguably lower than many un-cabled Ge-doped G652 SMFs. The results are significant because the 1310 nm they agree with predictive models of lower loss mechanisms in NANF that can be exploited across the C + L band operating spectrum and potentially at longer wavelengths.

Lower: Nonlinearity & Flatter Dispersion

NANF has lower nonlinearity (1000x lower than SMF), virtually eliminating distortion penalties that tend to dominate in un-regenerated long-haul, high bit-rate DWDM systems, namely self- and cross-phase modulation (SPM) and (XPM) respectively, and four-wave mixing (FWM).

The trend in long-haul systems has been to utilise the higher C band dispersion of SMF to help mitigate these penalties and electronic DSP at the receiver to compensate and recover signal quality. NANF in contrast has >6x lower and flatter dispersion in the C band and beyond 1700 nm and could have less need for receiver DSP.

Attenuation, Reach & Capacity

Nonlinear distortion degenerates signal-to-noise-ratio (SNR) and limits the extent to which higher launch powers can be used with SMF to extend system reach over long distances. Any improvement in SNR, gained through lower noise generation within HCF and/or injection of higher signal power, increases reach and boosts transmission capacity, according to this simplification of Shannon's Limit theorem (see Eq. (1)), where B, in Hz is the available bandwidth.

$$Capacity = B \log_2(1 + SNR) \qquad (1)$$

Modulation schemes that are more spectrally efficient and able to support higher bit-rates, pose challenges to the overall capacity-reach of single-mode systems, and there is usually a trade-off with greater reliance upon electronic DSP at the receiver to avoid compromising on reach.

NANF can tolerate ~1000x more optical power and in the absence of nonlinearity, could potentially extend un-repeatered total reach. Furthermore, distances between in-line amplifiers (ILA) could be increased.

Collaborative and independent studies including those by the University of Southampton and Politecnico di Torino, have used NANF and CoreSmart cable test data and computer simulations to predict data carrying capacity compared to SMF. Fig. 4 shows the predicted capacity vs transmission distance for a variety of different NANF attenuation values, optical launch power levels and signalling spectral efficiency of between 10 and 14 bits per symbol[7]. The assumptions here include the availability of extended wavelength range transceivers and higher power amplifiers (1500~1700 nm). These could help to realise greater capacity throughput of NANF (as compared to SMF) of between >2.5x for 100 km to over 5x greater capacity at 4000 km, without regeneration.

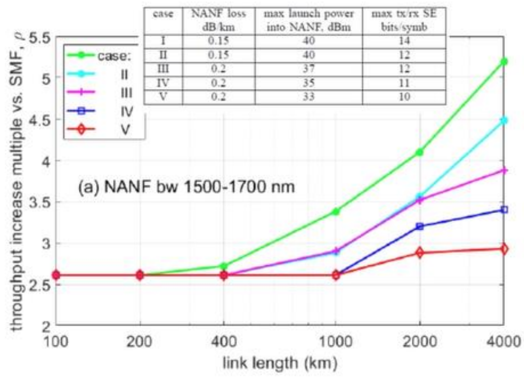

Fig. 4: Predicted capacity of NANF compared to SMF[7].

Conclusions

NANF CoreSmart cables have been tested and field deployed in the longest links ever achieved with HCF technology. Using lower attenuation NANF, CoreSmart cables are being developed for longer metro-DCI installations. More recent progression in further lower loss NANF, suggests potential for use in ultra-long-haul systems with up to 2x or greater transmission capacity vs current single-mode.

Acknowledgements

The authors wish to thank euNetworks for equipment used in latency study, Prof. P. Poggiolini and Dr. A. Nespola at Politecnico di Torino, and the ORC at the University of Southampton.

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