Real-Time, Fully-Loaded C-band, Low-Latency, Long-Haul Transmission over Hollow-Core Fiber

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Abstract *We investigate real-time, long-haul HCF transmission up to 11,154 km using ~360-km recirculating loop with ~120-km average span length and 34.5-dBm launch power. Data-rates of 25.6 Tb/s@ 1,439.2 km, 20.6 Tb/s@2,878.4 km are achieved with fully loaded ~130-Gbaud C-band signals and 10.3 Tb/s beyond 6,000km. ©2025 The Author(s)*

Introduction

Hollow-core fibers (HCFs) have demonstrated optical losses well below conventional silica single-mode fibers (SMFs) [1,2] and offer a range of beneficial optical transmission characteristics such as >30% reduced latency and low chromatic dispersion [3-5]. Further, the ultra-low non-linearity allows orders of magnitude higher launch powers than glass-core fibers, enabling significantly longer span lengths. This makes HCFs especially suited to long-haul (LH) systems, requiring fewer repeaters and offering >1.5 ms per 1000 km latency reductions compared to SMF systems.

Previously, HCFs combined with high power erbium-ytterbium doped fiber amplifiers (HP-EYDFAs) were shown to support metro transmission with ultra-long span lengths [6]. However, long-haul HCF transmission studies to date have typically used short HCF span lengths or focused on narrow spectral regions with negligible impact from gas line absorption (GLA) [5,7,8]. Further, many reported fibers exhibit inter-modal interference (IMI), polarisation mode-dispersion (PMD), and polarisation dependent loss (PDL) levels that limit their suitability for LH transmission [5,9,10].

Here, we investigate state-of-the-art real-time LH transmission of full C-band signals over double nested anti-resonant nodeless fiber (DNANF) for the first time. We use HP-EYDFAs to enable repeatered transmission with >34 dBm launch power. Using ~360 km of spooled and cabled fibers with reduced GLA levels drawn for metro applications, we transmit 32×150-GHz spaced, dual-polarization quadrature-amplitude modulation (DP-QAM) signals up to ~130 GBaud over >7,000 km, before investigating an 8-channel system over distances exceeding 11,000 km. We record a metro-scale data-rate of 25.6 Tb/s at 1,439.2 km, and data-rates of 20.6 Tb/s and 10.3 Tb/s at distances of 2,878.4 km and 6,116.6 km, respectively. Finally, we confirm ~31.49% reduced latency compared to SMF using request-for-comment (RFC) 2544 latency measurements.

Figure 1 compares these results with both reported HCF demonstrations and with real-time LH SMF demonstrations for ≥100 km span lengths. We note that few real-time SMF system

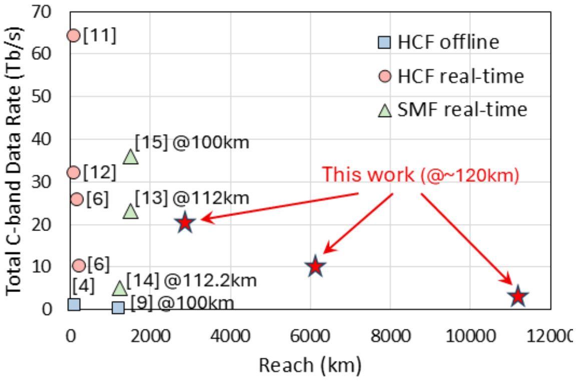

Fig. 1: ≥100 km span length demonstrations of real-time HCF/SMF transmission and offline HCF transmission

demonstrations with this spacing have been reported, particularly over longer distance, whereas state-of-the-art commercial subsea cables such as MAREA are designed with 56-km span lengths [15]. For commercial terrestrial links, span lengths vary greatly with a study of the Azure Network showing the vast majority of LH routes being < 2,000 km with spans ranging from 50 km to 105 km. The study shows that 65 km is the most common span-length and high-power distributed Raman amplification required for longer spans [17]. Our results show HCFs can already support low latency LH systems with large repeater spacing in next-generation networks, particularly for terrestrial LH scales.

Experimental Set-up

The experimental set-up for the ~360-km recirculating HCF loop is shown in Fig. 2(a). At the transmitter (Tx), a channel-under-test (CUT) was generated from a wavelength-tunable commercial-grade transceiver mounted on an evaluation board that supports gated operation. This channel was combined with 23 equivalent real-time optical signals and amplified before passing through an acousto-optic modulator (AOM) used to gate the loop input signals. Inside the loop, the 24 channels were combined with a further 8 non-gated, real-time channels located at the C-band edge furthest from the CUT and used to protect from amplifier gain transients during loop switch-on and shut-down. The HP-EYDFAs provided

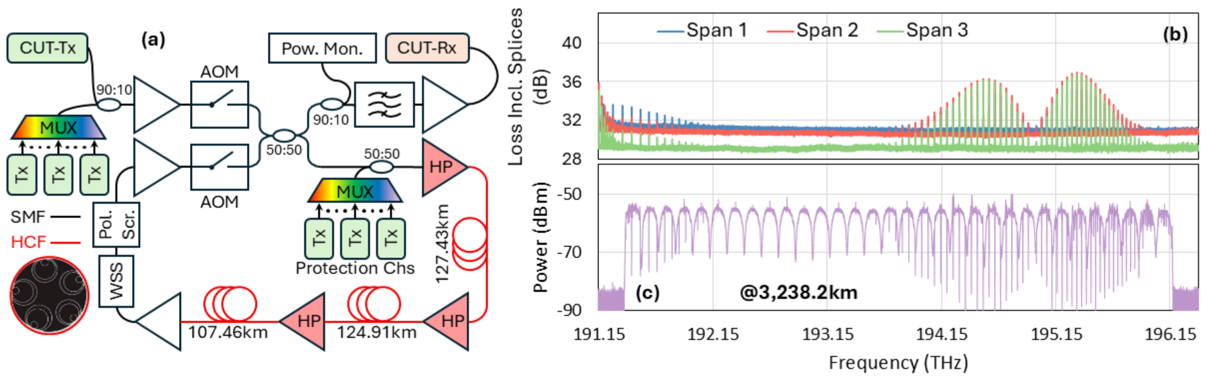

Fig. 2: (a) Experimental set-up, (b) loss profiles of 3 fiber spans with a spectral resolution of 25 MHz, and (c) optical spectra after 3,238.2 km with a resolution of 150 MHz.

34.5-dBm launch powers to the three HCF spans. These spans were followed by a wavelength-selective switch (WSS) to adjust the signal spectra and a loop-synchronous polarization scrambler. Two additional 23.5-dBm EDFAs were used to compensate for the non-fiber loop losses. The loop switch used two cascaded AOMs with opposite frequency shifts to ensure net zero frequency shift for the circulating signals. At the receiver (Rx), a tunable filter was used to select the CUT for performance analysis. The CUT used Baud rates up to ~130 GBaud and generated/detected data rates varying from 400 G/s to 1.1 Tb/s in 100 Gb/s steps. For all measurements, each of the 32 channels traversed the 3 fiber spans, whilst the protection channels at the band edge furthest from the CUT were filtered out by the WSS. To test the ultimate transmission limits, a further experiment with 8 consecutive channels least affected by GLA (i.e., 192.35 THz to 193.4 THz) was also conducted.

The span lengths of 127.43 km, 124.91 km and 107.46 km were measured through bi-directional optical time-domain reflectometer measurements [6]. The first two spans were made up of 43 bobbins holding fibers of lengths ranging from ~2 km to ~17.9 km with an average length of ~5.87 km, a distance representative of splice frequency in field installations. The 107.46 km span was made up of spliced fibers housed in 2 HCF cables of ~3-km and ~4-km lengths. All these fibers were of a DNANF design with 5 sets of nested resonator tubes. The fibre structure is shown in the inset of Fig. 2(a), which is similar to that reported in [1,2]. The fibers operated in the fundamental anti-resonant window, and the measured IMI of all individual fibers used in these experiments was below -56 dB/km. The measured chromatic dispersion ranged from around 3.83 to 4.04 ps/nm/km, and the mean PMD values of the three spans were around 0.17 and 0.12 ps/$\sqrt{km}$, for the 2 spooled fiber spans and 0.29 ps/$\sqrt{km}$ for the cabled fibers. Fig. 2(b) shows the loss performance of the three spans in the C-band, and the average losses (including all HCF-HCF splice losses) were around 0.24, 0.24, and 0.27 dB/km, respectively. Furthermore, GLA due to the presence of carbon-dioxide in the fiber core can also be seen on the loss profile, which corresponds to maximum absorption peak component values of 0.03, 0.05, and 0.07 dB/km at the highest absorbing C-band frequency of ~195.33 THz for the 3 spans, respectively. The impact of GLA on transmission spectra after 3,238.2 km is shown in Fig. 2(c).

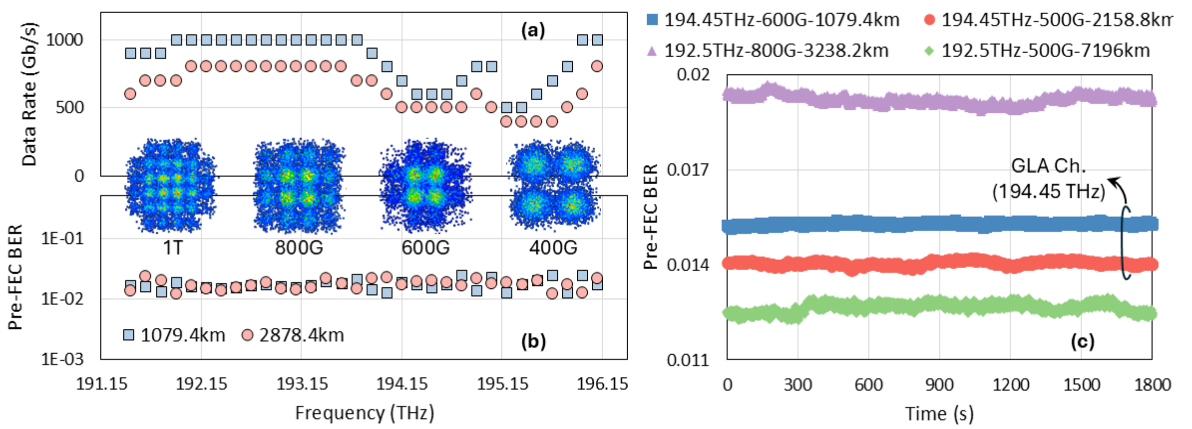

Fig. 3: (a) Data rate versus frequency in the C-band after 1,079.4 km and 2,878.4 km and (b) the corresponding pre-FEC BERs, and (c) pre-FEC BERs versus time at two representative channels under different data rates and distances. Insets: constellation plots of 1T, 800G, 600G and 400G transmission.

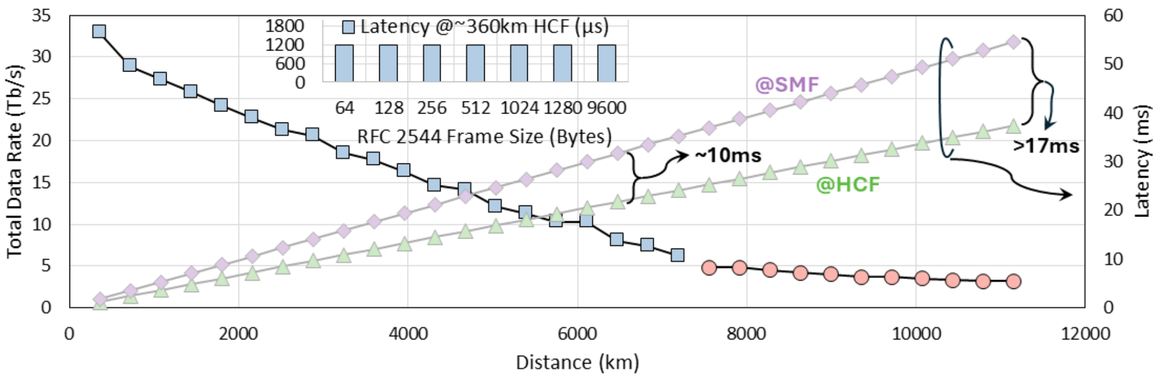

Fig. 4: Total data rate and latency versus distance. Inset: measured latency of the 3 spans of DNANF using RFC 2544 test.

Experimental Results and Discussions

Figure 3(a) shows the total measured data rates for the 32 channel C-band system after 1,079.4 km and 2,878.4 km transmission. Although the figure shows that the link GLA level is sufficiently low for full C-band LH transmission, for both distances the achievable data-rates were determined by the GLA level, matching the profile evident in Fig. 2(c). After 1,079.4-km transmission, the channel data rate varied from 1 Tb/s to 500 Gb/s whereas it ranged from 800 Gb/s to 400 Gb/s after 2,878.4 km transmission. The corresponding pre-forward error correction (pre-FEC) bit error rates (BERs) were all below the FEC limit of 2.4×10^{-2}, as shown in Fig. 3(b). For reference, the constellation plots of 1 Tb/s, 800, 600, and 400 Gb/s are shown as insets in Fig. 3. We further evaluated the pre-FEC BER performance stability over time at one channel with high GLAs (194.45 THz) and one channel without any observable GLA impairment (192.5 THz). Pre-FEC BERs were captured every second over a 30-min duration, and stable pre-FEC BERs were observed at different data rates and distances, as shown in Fig. 3(c).

Figure 4 shows the measured total data rate of the 32 and 8 channel systems as a function of distance up to 11,154 km. For 1,079.4 km the measured data rate was 27.3 Tb/s and the 25.6 Tb/s typical of metro systems was achieved at 1,439.2 km, showing the potential of HCF systems for high data-rate terrestrial LH systems such as inter-data center links. Additional milestones were a total 20.6 Tb/s at 2,878.4 km, 10.3 Tb/s after 6,116.6 km and over 6.2 Tb/s at 7,196 km. Beyond this, the 8-channel system (circles in Fig. 4) was measured to support 4.8 Tb/s after 7,555.8 km and 3.2 Tb/s after 11,154 km, the longest reported HCF transmission to date.

Finally, we measured the latency of the loop fiber spans using the RFC 2544 test. As shown in the inset of Fig. 4, the total latency was around 1,205.5 µs (~3.35 µs/km), excluding ~6.45-µs measured transceiver latency. In comparison, the SMF's latency was measured to be ~4.89 µs/km through a ~161.43 km link. The latency comparison between DNANF and SMF is also illustrated in Fig. 4, which shows a significant ~10-ms latency reduction (~31.49%) after 6,476.4 km transmission and >17 ms for the longest measured distance of 11,154 km.

We note that the fibers utilised here were drawn at volume for metro applications and considerable scope for loss reduction to allow for further increased repeater spacing exists. Indeed, more than two-fold reduction in both fiber loss and GLA from CO_2 can already be achieved in R&D fibers [1,2]. In addition to reducing CO_2 levels, further system-level mitigations such as optimized channel allocation, and customized digital signal processing remain. However, our results show that exploiting low nonlinear interactions with increased launch power can already facilitate both terrestrial LH distances and beyond with ~120-km span compatible with standard real-time commercial transceivers. These results show the potential of HCFs to support high-data-rate long haul systems with repeater spacings that are not viable with standard fiber. Further, we have confirmed that such links can deliver significantly reduced latency, making them particularly attractive for latency-sensitive AI related applications [18].

Conclusions

We have demonstrated full C-band real-time LH HCF transmission over transoceanic distances, employing recirculating transmission with ~120-km average span length of low GLA HCF and 34.5-dBm launch power for the first time. We measure a standard metro data-rate of 25.6 Tb/s after 1,439.2 km and 20.6 Tb/s after 2,878.4 km with fully loaded C-band signals. Further, the system shows latency improvement over SMF of ~1.54 ms per 1000 km reaching >17 ms at 11,154 km. These results bring the prospect of low-latency, long-haul fiber systems with large repeater spacing built on HCFs firmly into view.

Acknowledgements

We thank the Azure Fiber and AI HCF manufacturing and cabling teams for provision of all fibers and cables used in this work.

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