Comparative Investigations between SSMF and Hollow-core NANF for Transmission in the S+C+L-bands

Yang Hong, Thomas D. Bradley, Natsupa Taengnoi, Kyle R. H. Bottrill, John R. Hayes, Gregory T. Jasion, Hans C. Mulvad, Francesco Poletti, Periklis Petropoulos, and David J. Richardson
Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom
Author e-mail address: y.hong@soton.ac.uk

Abstract: An experimental study reveals that hollow-core nested anti-resonant-nodeless fibers exhibit a broader bandwidth, lower latency, and offer >20% capacity enhancement in short-reach >100-Gb/s adaptively-loaded DMT transmission, relative to a standard SMF of a similar length.

1. Introduction

The traffic in intra-datacenter interconnects (DCI) with a reach ranging from hundreds of meters to up to a few kilometers accounts for more than 80% of today's total Internet traffic. Coherent transmission systems are generally still considered too costly for such applications, despite the benefits they offer in terms of receiver sensitivity and spectral efficiency. Therefore, intensity modulation and direct-detection (IM/DD) implementations are largely preferred thanks to their simplicity and cost-effectiveness [1, 2]. The main performance limiting factor in high-speed IM/DD systems over standard single-mode fiber (SSMF) is chromatic dispersion (CD)-induced power fading [2]. For example, it is straightforward to show that the transmission spectrum will exhibit a first frequency null at ~27 GHz over a 5-km 1550-nm transmission in SSMF. Optical dispersion compensation (e.g. through the use of dispersion compensating fiber) whilst clearly possible is considered unsuitable over such distances, and the CD effects are generally mitigated through the use of spectrally-efficient modulation formats, such as Nyquist 4-ary pulse amplitude modulation (PAM4) or adaptively-loaded discrete multitone (DMT) [2, 3]. However, as the need for ever higher transmission speeds intensifies, the limited bandwidth of the SSMF becomes the main obstacle to the scalability of IM/DD systems.

The development of disruptive fiber technologies, such as hollow-core fibers, provides a fundamentally different route to minimizing the effect of CD over an ultrawide bandwidth [4], whilst at the same time offering exceptionally low transmission latency, thanks to the guidance in an air core, which is also of primary concern in short-reach DCIs. In this paper, we compare the bandwidth, latency and data transmission performance of SSMF and a hollow-core nested antiresonant nodeless fiber (NANF) over the S+C+L-bands. While the loss of the NANF is currently higher than that of conventional fibers, we show that over a 5-km distance, the NANF's overall performance with respect to CD, bandwidth and latency is already superior. Furthermore, based on experiments using a ~5-km span of NANF, we demonstrate that the fiber allows for penalty-free 100-Gb/s Nyquist PAM4 transmission and offers more than 20% capacity enhancement in adaptively-loaded DMT transmission over a SSMF of a similar length.

2. Structure of the NANF and Numerical Simulations

Fig. 1(a) shows cross-sectional scanning electron microscope (SEM) images of two structurally matched NANFs, which were individually fabricated and spliced together to produce a spool of ~5 km length. Both fibers operate in the first antiresonant window. The average core size and membrane thickness of the first 3.4-km length of NANF (#1) were 36.4 μm and 0.55 μm, respectively, whilst the corresponding values of the second 1.39-km length of NANF (#2) were 34.6 μm and 0.50 μm, respectively. To incorporate the NANF into a SSMF-based system, at both ends of the NANF, a mode field adaptor was spliced in between the NANF and an SSMF patch cord whilst the two NANFs were directly spliced together. These multiple splices contributed around 2 dB to the total measured insertion loss of the spool, which ranged between 7-8 dB across the S+C+L-bands, as will be shown in the experimental results below.

We first compare the simulated CD of the NANF to that of the SSMF (*ITU G.652*). Note that the mean value of the range of CD as specified in the ITU standard was used for each wavelength in the SSMF case. As shown in Fig. 1(b), the NANF exhibits a much lower CD (and a much lower CD slope) than the SSMF across the 1400 nm to 1625 nm wavelength range. Accordingly, the numerical results of the 3-dB bandwidths of 5-km lengths of NANF and SSMF are shown in Fig. 1(c). Here, the bandwidth of the fiber was obtained by considering the CD-induced power fading. It is seen that compared to the SSMF, the NANF exhibits more than twice the bandwidth across the 1400 nm to 1600 nm wavelength range. For reference, the CD and bandwidth performance of the non-zero dispersion shifted fiber (NZ-DSF – *ITU G.655*) is also included in Fig. 1(b) and (c), respectively, confirming that the NANF also offers a broader bandwidth across all wavelengths, apart from a 60-nm range around 1460 nm, where the CD of the NZ-DSF approaches zero. It is also worth noting that over this same distance the NANF offers a ~8-µs reduction in latency compared to the solid-core fibers, as shown in Fig. 1(d).

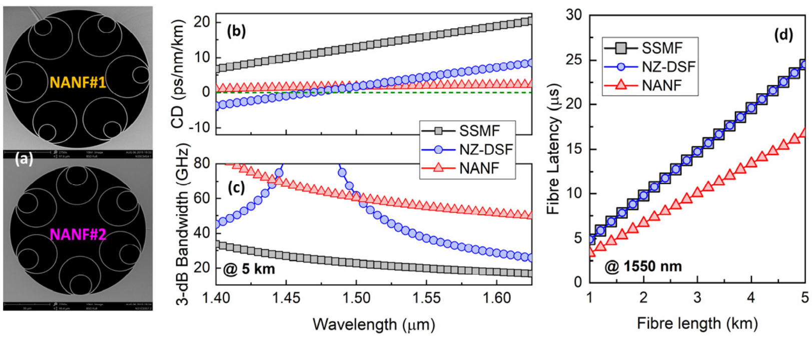

Fig. 1. (a) SEM images of the fabricated NANFs, and comparison amongst the SSMF, NZ-DSF and NANF at a length of 5 km: (b) CD, (c) 3-dB fiber bandwidth, and (d) latency arising from the transmission in the fiber.

3. Experimental Setup and Results

We implemented an IM/DD transmission system to further compare the performance of the ~5-km NANF to that of a similar length of SSMF. In the DD system, a tunable laser was used to generate an optical carrier over the range 1460 nm to 1640 nm, which was fed into a Mach-Zehnder modulator (MZM). The electrical signal used to modulate the MZM was first generated by an arbitrary waveform generator (AWG) and then amplified by an electrical amplifier. The output of the MZM was directly launched into the transmission link (B2B/NANF/SSMF) without optical amplification. At the receiver, an optical attenuator was used to vary the received optical power (ROP) at the photodetector (PD), and the detected signal at the PD was captured by an 80-GSa/s digital storage oscilloscope for further offline digital signal processing.

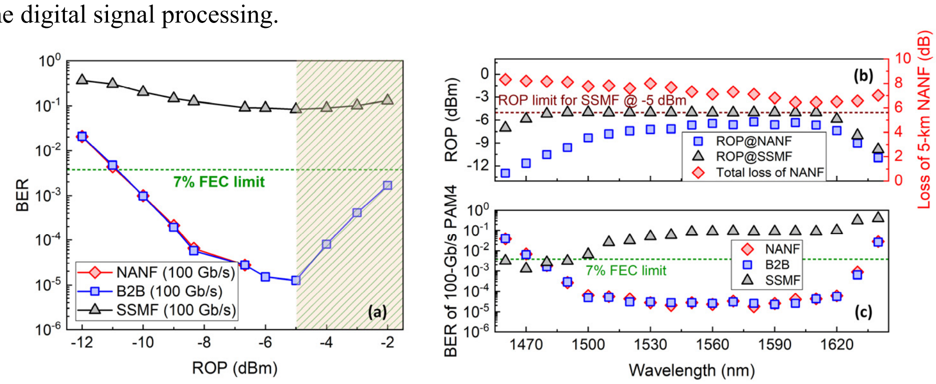

Fig. 2. (a) BER versus ROP at 1550 nm for the 100-Gb/s PAM4, and wavelength sweeping over S+C+L-bands: (b) ROP in different cases and measured total loss of the ~5-km NANF, (c) BER versus wavelength of the 100-Gb/s PAM4.

Fig. 2(a) shows the bit error rate (BER) performance of 100-Gb/s Nyquist PAM4 at 1550 nm in the three cases. It is seen that similar BERs as in the B2B can be achieved by the NANF, confirming the ultra-low CD of the fiber. At a ROP greater than -11 dBm, a BER below the 7% forward error correction (FEC) limit, i.e., 3.8×10^{-3}, can be achieved. In contrast, regardless of the ROP, the BER measured when transmitting in the SSMF is always above the 7% FEC limit, which results from the severe fading within the signal's bandwidth (~25 GHz) due to the CD effect. Note that a degraded BER performance is obtained at ROPs greater than -5 dBm, because of the limited input range of the transimpedance amplifier in the PD. We further tune the laser across the S+C+L-bands in all three cases. As shown in Fig. 2(b), the total insertion loss of the ~5-km SMF-connectorized NANF over the S+C+L-bands ranged around 7 to 8 dB which included the aforementioned ~2-dB splicing loss. The corresponding ROPs for the two cases are also given in Fig. 2(b), which indicates that the reduced ROP at the edges of the tuning range were caused by the limited output power of the laser at these wavelengths. Note that to avoid a high ROP-induced performance degradation (as observed in Fig.2(a)), a ROP limit of -5 dBm was applied in the SSMF case. The BERs of 100-Gb/s PAM4 transmission across the S+C+L-bands are shown in Fig. 2(c). Note that the ROP in the B2B case was attenuated to the same level as in the NANF case for comparison. Similar BERs can be achieved over the S+C+L-bands for the NANF compared to the B2B case. For most of the wavelengths in the S+C+L-bands, a BER lower than the 7% FEC limit can be achieved. In contrast, in the SSMF case, only a few wavelengths at the beginning of the S-band can marginally achieve a BER below the 7% FEC limit. Furthermore, the BER gets worse with increasing wavelength, despite the ROP being maintained around -5 dBm. This reflects the fact that the CD effect becomes more severe at longer wavelengths.

Without loss of generality, we take the 1550-nm wavelength as an example to further investigate the impact of CD on the transmission performance in SSMF and NANF. Here, DD optical orthogonal frequency division multiplexing (DDO-OFDM) is adopted, as its signal bandwidth can be flexibly adjusted, and it offers the capability of capacity maximization using adaptive loading. As shown in Fig. 3(a), the NANF offers a lower BER than the SSMF, yet the difference is less significant when a small number of data subcarriers, i.e., a narrow signal bandwidth, is used. This is because the CD-induced fading is less severe at low frequencies. Fig. 3(b) and Fig. 3(c) show a comparison of the signal-to-noise ratio (SNR) profiles after transmission in the 5-km SSMF and ~5-km NANF, respectively. The number of data subcarriers is 240, which corresponds to a signal bandwidth of 32.8125 GHz. It is clear that severe fading within the signal's bandwidth is experienced in the SSMF case, whilst no such fading is observed in the NANF case. Note that the two low-SNR spikes in Fig. 3(c) as well as Fig. 3(b) were caused by clock leakage of the AWG rather than any of the fibers. For reference, the corresponding SNR profiles when using adaptive bit-and-power loading, i.e., the adaptively-loaded DMT, are also provided. Finally, with a signal bandwidth of 32.8125 GHz, i.e., 240 data subcarriers, by using bit-and-power loading, we also investigated the maximum capacity of the 5-km length of SSMF-/NANF-based transmission. As shown in Fig. 3(d), the NANF can offer around 20% to 30% capacity enhancement over the SSMF while operating within the 7% FEC limit (Fig.3(e)).

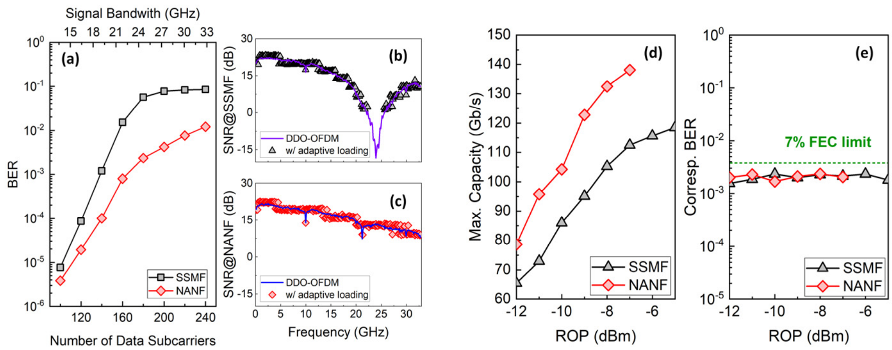

Fig. 3. Comparison between the SSMF and NANF using DDO-OFDM at 1550 nm: (a) BER versus number of data subcarriers; SNR profiles after 5-km transmission in (b) SSMF and (c) NANF; (d)&(e) comparison of the maximum capacity and the corresponding BER.

4. Conclusion

In this paper, we performed a comparative study of the performance of SSMF and NANF over the S+C+L-bands. Simulation results showed that the NANF can offer a lower CD and thus a wider bandwidth than the SSMF. Furthermore, our experimental results validated that the NANF allows for penalty-free 100-Gb/s PAM4 transmission over a length of ~5-km. More than 20% capacity enhancement can be achieved relative to SSMF in the adaptively-loaded DMT transmission at this distance, showing a promising route to realizing higher capacity with ultra-low latency in future optical interconnects.

This work was supported by the UK's EPSRC under the Airguide Photonics Programme grant (EP/P030181/1), the COALESCE project (EP/P003990/1), as well as through the ERC Lightpipe project (682724).

5. References

[1] J. Cheng, *et al*., "Comparison of Coherent and IM/DD Transceivers for Intra Datacenter Optical Interconnects," *OFC*, paper W1F.2, 2019.
[2] X. Pang, *et al*., "Beyond 200 Gbps per Lane Intensity Modulation Direct Detection (IM/DD) Transmissions for Optical Interconnects: Challenges and Recent Developments," *OFC*, W4I.7, 2019.
[3] D. Pilori, et al., "Comparison of Probabilistically Shaped 64QAM With Lower Cardinality Uniform Constellations in Long-Haul Optical Systems," *JLT*, 36(2), 501-509, 2018.
[4] T. D Bradley *et al.*, "Antiresonant hollow core fibre with 0.65 dB/km attenuation across the C and L telecommunication bands," *Proc. of ECOC*, post-deadline paper, PD 3.1, 2019.