Simultaneous C/L-band Power and Data Delivery over 3.1km of NANF

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Abstract: We show that hollow-core fibre outperforms single-mode fibre at three-channel 28 GBd DP-16QAM transmission when copropagating with an up to 37.5 dBm feed. There is no sign of power-dependent signal degradation in the hollow-core fibre. © 2024 The Author(s)

1. Introduction

Moving towards an all-fibre communication network offers economic savings through both reduced cable ownership and deployment costs. Unfortunately, the need to remotely deliver both power and data, often driven by concerns of network resilience to power failure, necessitates the continued deployment of copper cabling in many cases, obstructing progress in this direction.

A natural solution to this challenge is to deliver not only data-over-fibre, but also power-over-fibre (PoF), a strategy that has been gaining increased interest as of late, as development is accelerated by recent advancements in novel optical fibre technology. Contending fibre designs included multimode fibre [1], double-clad fibre [2], multicore fibre [3,4], hollow-core fibre [5,6], and photonic crystal fibre [7]. Each approach has its advantages, but notably, hollow-core fibre permits both power and data to co-propagate in the same fundamental spatial mode unimpeded over long distances, due to its exceptionally low nonlinearity and high power handling. Indeed, hollow-core fibre (HCF) has been shown to have an especially high power-handling of upwards of 1 kW [8] without exceeding the nominal temperature limit of fibre coating near the point of coupling [9], and without incurring high losses. Propagation loss will be a critical deciding factor when it comes to designing future PoF systems and, importantly, not only has HCF been shown to have the lowest propagation loss of any fibre, at 0.11 dB/km [10], but it can be engineered to transmit at low loss at wavelengths of choice.

Recently, we demonstrated the concurrent transmission of 43 mW of power at ~800 nm alongside a 10Gbps OOK at 1550 nm, enabled by exploiting two transmission windows of a nested antiresonant nodeless fibre (NANF) [11]. This approach has its advantages in that it enables the use of high power Watt-level Silicon and Gallium Arsenide photovoltaic laser power converters for optical-to-electrical power conversion. However, such a dual-window approach strains currently available passive componentry, presenting challenges to multiplexing and compromising insertion loss (a critical factor when considering PoF systems). Furthermore, high-power single-mode sources are currently challenging to obtain in this wavelength region, a fact compounded by a relative lack of suitable fibre dopants with only Neodymium offering gain in this region, albeit with examples exhibiting poor wall-plug efficiency for widespread application in communications networks [12].

In this work, we choose to circumvent these issues by exploiting that exceptionally low nonlinearity of hollow-core fibre, locating both the power and data feed in the same antiresonant window of a NANF, separated by only 26 nm. This approach greatly simplifies multiplexing and power feed generation, allowing off-the-shelf telecommunications components to be used, with single-mode power provided by the ubiquitous Erbium doped fibre amplifier (EDFA). This enables us to demonstrate the delivery of 750 mW of optical power over 3.1km simultaneously with a 3x28 GBd dual-pol. 16QAM dense wavelength division multiplexing (DWDM) band (with an aggregate bit rate of 672 Gbit/s), observing no penalties to received signal quality with increasing power feed. For reference, we compare this demonstration to propagation in 4 km of SMF28e+ fibre and observe performance degradation for as little as 110 mW of delivered optical power.

2. Experimental setup

The fibre under investigation is a 3.1 km HCF with 5 dB combined insertion and propagation loss in the C and L-bands. The fibre has mode field diameter adapting splices to single-mode fibre (SMF), allowing it to be readily used with commercial pigtailed components. Its cross section is shown in Fig. 2, right.

The setup for the demonstration is given in Fig. 1. Three signal channels: λ_1=1571.24 nm, λ_2=1569.59 nm, and λ_3=1571.24 nm, corresponding to 100 GHz DWDM Grid ITU channels 10, 9, and 8 respectively, were generated with L-band laser sources. The channels were modulated with a root-raised cosine (with roll-off of 0.35) filtered 28 GBaud

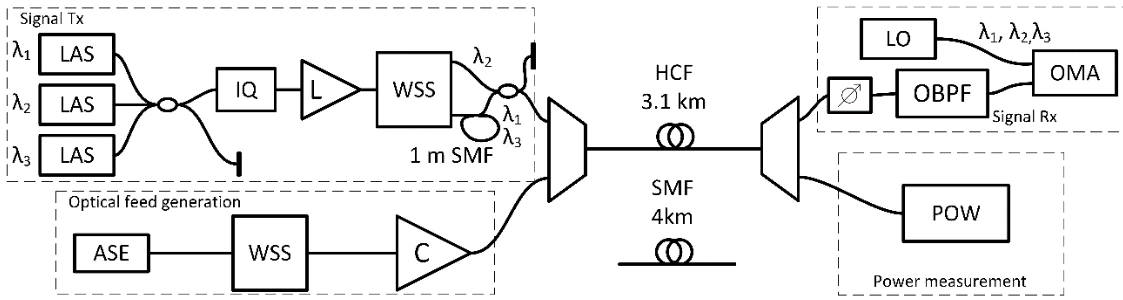

Fig. 1. Left: Experimental setup for provision of OF channels and data channels. LAS – tuneable laser, IQ – coherent dual-pol. modulator, ATT – attenuator. Right: Spectrum of seed fed to EDFA for OF generation.

DP-16QAM signal to carry a $2^{15} - 1$ PRBS (net bit rate 672 Gbps) and amplified to 16 dBm using an L-band EDFA. To decorrelate the data carried by the DWDM band, the middle channel was demultiplexed from the outer two, which were passed over a 1 m SMF patchcord before being remultiplexed using a 50:50 coupler for a launch power of -5.8 dBm per channel. To create the optical power feed (OPF), C-band amplified spontaneous emission (ASE) was filtered by a WSS to create a 100 GHz wide, flat-topped seed (a spectrum of which is provided in the left plot of Fig. 2), centred at a wavelength of 1544.53 nm (ITU Ch. 41) to minimise stimulated Brillouin scattering by the amplifier and the link. The seed was amplified by a 5-W C-EDFA to form the OPF. This was then multiplexed with the DWDM band using a 200 GHz add-drop multiplexer to further suppress any spurious out-of-band ASE. The loss between the C band EDFA and the fibre was 1.74dB.

With the OPF and data multiplexed, they could then be transmitted over the test fibre, either 4 km of SMF28e+ (with an insertion loss of 2 dB) or of 3.1 km NANF (with an insertion loss of 5 dB). The SMF length was selected to be as close to the NANF length as possible, accounting for spool availability in our lab. After transmission, the OPF and DWDM bands were demultiplexed using a C/L demultiplexer. The received optical power was measured using a power meter, whilst the centre channel (Ch. 9) of the DWDM band was selected using a ~50 GHz optical bandpass filter before being analysed with an optical coherent receiver using a local oscillator for intradyne detection. The signal was filtered using a matched, root-raised cosine filter and residual chromatic dispersion was compensated for by using an adaptive equalizer. The received symbols were analysed to determine the error vector magnitude (EVM) of the signal and bit counting was performed to determine the bit error ratio (BER).

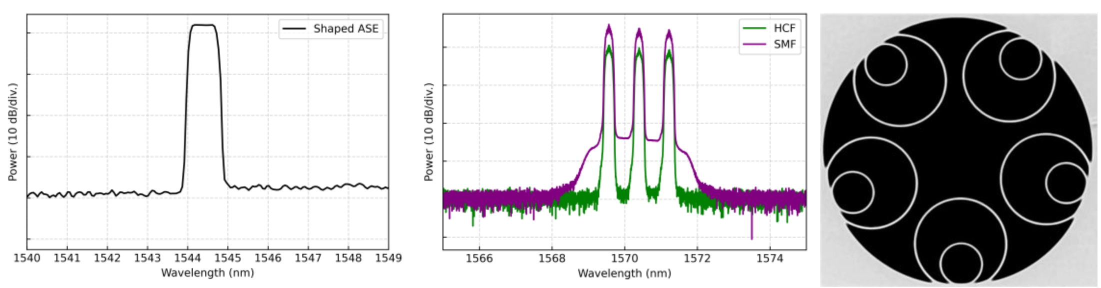

Fig. 2. Spectra measured with 0.07nm resolution - Left: Seed to C-EDFA for generation of OPF. Middle: HCF and SMF data signal spectra after demultiplexing, before the tuneable filter at the receiver. Right: Cross section of the NANF.

3. Results

To demonstrate the potential of the HCF for simultaneous data and high-power OPF delivery, the EVM of the received channel was measured for a range of OPF power levels (measured at the output of the C-EDFA) and compared to the results found using the SMF28e+ test fibre, as shown in Fig. 3a. When using the HCF, it can be seen that the performance of the system is largely agnostic to the input pump power, with the EVM remaining at ~8.8% rms all the way to a launched power of 37.5 dBm (5.6 W), corresponding to a received power of 28.8 dBm (0.74 W). Meanwhile, the SMF28e+ shows remarkably different behaviour, with the onset of degradation apparent even at the modest launched power level of 23.6dBm (0.3W), corresponding to a received power of 20.6 dBm (0.11 W).

Constellation diagrams of the 16QAM signal for an OPF of 27.7dBm (0.59 W) are shown in Fig. 3b and 3c, corresponding to EVMs of 8.8% and 12.7% respectively. Note the increase in phase noise in the SMF constellation, which is a result of cross-phase modulation (XPM) imposed by the OPF. This is corroborated by the spectrum in the right plot of Fig. 2, where XPM can be seen to have resulted in significant broadening of the signals in the SMF case compared to the HCF case, where no degradation is observable.

Finally, BER curves (see Fig. 3-d) were taken by varying the received optical power after transmission with an attenuator. Measurements are shown for the HCF transmission case, along with a back-to-back measurement obtained by bypassing the HCF. The results show an indiscernible power-penalty, showing the impressive linearity of the HCF.

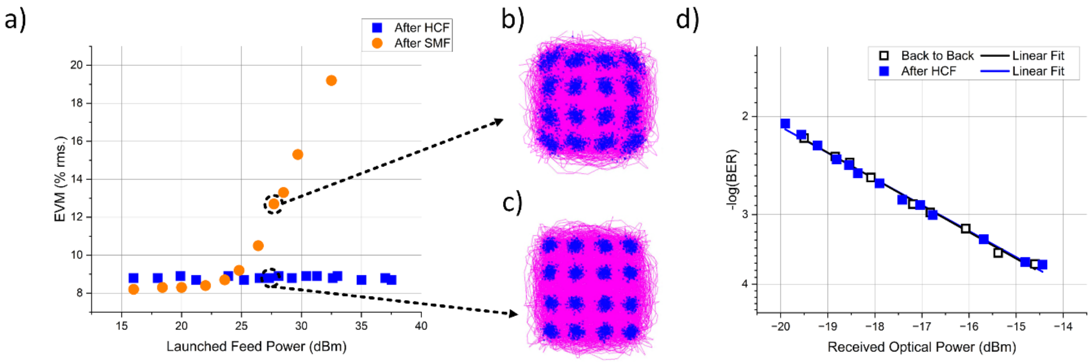

Fig. 3: a) EVM of λ_2 as it varies with launch power. b) and c) Constellation diagrams of λ_2 after propagation alongside 27.5dBm of pump power in 4 and 3.1 km of SMF28e+ and HCF, respectively. d) BER curves for back-to-back and after propagation in HCF.

4. Conclusions

This work has shown that HCF is a worthy candidate for high power optical feed delivery alongside high-capacity data transmission. The ability to power remote transceivers without power penalty induced on the signal is a promising sign that HCF will be highly competitive for PoF in resilient optical networks. We hope this work will contribute to motivating the development of Watt-level laser power converters at the longer wavelengths surrounding 1550nm, to allow better exploitation of pre-existing telecommunications hardware.

5. Acknowledgments

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6. References

[1] A. P. Goutzoulis, J. M. Zomp, and A. H. Johnson, 'Development and antenna range demonstration of an eight-element optically powered directly modulated receive UHF fiberoptic manifold', Journal of Lightwave Technology, vol. 14, no. 11, pp. 2499–2505, Nov. 1996
[2] Y. Yaguchi, Y. Miyakawa, S. Sugiura, S. C. Lin, S. Subramaniam, H. Hasegawa, S. Fafard, D. Masson, M. Matsuura, "Power-Over-Fiber Using a Pure-Silica Inner-Cladding Double-Clad Fiber and 976 nm Photovoltaic Power Converter for Improving Power Transmission Efficiency", *ECOC 2024, 2024*
[3] M. Wada, K. Kurokawa, T. Matsui, H. Iida, and K. Nakajima, 'High-Efficiency and Long-Distance Power-over-Fibre Transmission using a 125-um Cladding Diameter 4-Core Fibre', *ECOC 2023, 2023*
[4] C. Vázquez et al., 'Multicore Fiber Scenarios Supporting Power Over Fiber in Radio Over Fiber Systems', IEEE Access, vol. 7, pp. 158409–158418, 2019
[5] S. Suguira, K. Murakami, Y. Gomi, T. Takagi, K. Mukasa, M. Matsuura, "Demonstration of Power-Over-Hollow-Core-Fibre With 5G NR Signals for Optically Powered Remote Antenna Units", *ECOC 2024, 2024*
[6] R. A. Perez, Y. Jung, P. Petropoulos, and C. Vazquez"Power Over Fiber and Analog Radio Over Fiber Simultaneous Transmission Over Long Distance in Single Mode, Multicore, and Hollow Core Fibers" in *Laser and Photonics Review 18(8)*, June 2024
[7] K. Omoto, N. Hanzawa, M. Wada, K. Kurokawa, T. Matsui, K. Nakajima, "Applicability of 125-um cladding diameter quasi-single-mode photonic crystal fibre link for power-over-fibre and data transmission", *ECOC 2024, 2024*
[8] H. C. Mulvad et al., 'Kilowatt-average-power single-mode laser light transmission over kilometre-scale hollow-core fibre', Nature Photonics, vol. 16, Jun. 2022
[9] R. Janani et al., 'From acrylates to silicones: A review of common optical fibre coatings used for normal to harsh environments', Progress in Organic Coatings, vol. 180, p. 107557, Jul. 2023
[10] Y. Chen et al., "Hollow Core DNANF Optical Fiber with <0.11 dB/km Loss", *OFC 2024*.
[11] D. McCulloch, K. R. H. Bottrill, Y. Jung, I. A. Davidson, H. C. Mulvad, H. Sakr, J. Meng, F. Poletti, P. Petropoulos, "Simultaneous Power and Data Transmission over 1.21 km of Nested Antiresonant Nodeless Fibre", *ECOC 2024, 2024*
[12] S. Rota-Rodrigo et al., 'Watt-level single-frequency tunable neodymium MOPA fiber laser operating at 915–937 nm', Opt. Lett., OL, vol. 42, no. 21, pp. 4557–4560, Nov. 2017