8.96Tb/s (32×28GBaud×32QAM) Transmission over 0.95 km 19 cell Hollow-Core Photonic Bandgap Fiber

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Abstract: The longest coherent transmission distance of 0.95km, and highest distance×bandwidth product 19cell hollow-core photonic bandgap fiber (HC-PBGF) are demonstrated, indicating the potential for longer distance HC-PBGF high capacity coherent transmission applications.
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1. Introduction

As standard solid-core single mode fibers are predicted to reach their intrinsic capacity limits in the upcoming years, ultra-low nonlinearity hollow-core photonic bandgap fibers (HC-PBGFs) may provide a viable solution to meet future capacity increase trends [1]. The potential increase in capacity-per-fiber offered by HC-PBGFs arises from the combination of the orders-of-magnitude increase in nonlinearity tolerance and the realistic prospect of opening up a new, wider transmission window at 2µm [2]. Additionally, due to the transmission at close to speed of light in vacuum, the potential of HC-PBGFs for ultra-low latency transmission has been clearly identified [3]. Recently, substantial progress has been reported on these HC-PBGFs, including increasing the transmission bandwidth through control of the surface mode resonances [2,3], and the development of large core designs, which are required to achieve ultra-low loss [4].

Through the aforementioned fiber improvements, the state-of-the-art transmission capacity of HC-PBGF has been steadily increasing. The most recent achievements are 30.7Tb/s dual polarization (DP)-32 quadrature amplitude modulation (QAM) transmission [5] and 73.7Tb/s DP-16QAM [6], in a 19 cell and 37 cell HC-PBGF, respectively. While the former only used a single mode, the latter employed 3 mode transmission. However, these record values were obtained using relatively short lengths of HC-PBGF (230m in [5], and 310m in [6]). Therefore it is of great importance to fully establish the performance of the HC-PBGF technology for longer fiber lengths, which become available as the fabrication technologies continue to improve.

In this work, coherent transmission over a record distance of 0.95km of 19 cell HC-PBGF is shown. Using only the fundamental mode and coherent transmission employing a low complexity 2×2 multiple-input multiple-output (MIMO) frequency domain equalizer (FDE), the transmission of a 32×224Gb/s DP-16QAM and a 32×280Gb/s DP-32QAM with gross bit rates of 7.2Tb/s and 8.96Tb/s are demonstrated, respectively. These values represent the longest HC-PBGF coherent transmission experiment, as well as the highest single-mode transmission bandwidth×distance product reported. The experiment demonstrates that the km-scale HC-PBGF length is already relevant to shorter reach data transmission applications, and shows that the HC-PBGF is becoming relevant for high data rate coherent communication systems.

2. Experimental Setup

The experimental setup is shown in Fig. 1a. To cover a large portion of the C-Band, 32 external cavity lasers (ECLs) placed on a 100 GHz ITU-grid ranging from 1537.4 nm to 1562.23 nm are used as loading channels. A separate ECL, which replaces one of the 32 lasers, is used as channel under test (CUT). The CUT laser output is split into two equal tributaries. One is used as local oscillator (LO) for the coherent receiver. The other acts as the transmitter laser, and is guided through a Lithium Niobate IQ-modulator, where it is modulated by a 28GBaud signal. The IQ-modulator is driven by two digital-to-analog converters (DACs), which represent the in-phase (real) and quadrature (imaginary) component of the transmitted constellations, respectively. The gray coded constellations used are 16 and 32QAM. The transmitted constellation sequences are formed in the digital domain by a number of fully uncorrelated pseudo random bit sequences (PRBSs), each of length 2^{15}. This allows additional correlations within the 2^{15} symbol sequence to be avoided, even after gray coding. The output of the IQ-modulator is split into two equal outputs. One arm is delayed by 1233 symbols with respect to the other for decorrelation at the polarization multiplexing stage. After recombining the two arms, a DP signal is obtained. This DP signal is particularly important to measure the polarization dependent loss. The signals are then guided through a wavelength selective switch (WSS), where the even and odd wavelengths are decorrelated by 10215 symbols. The decorrelated output is then launched into the

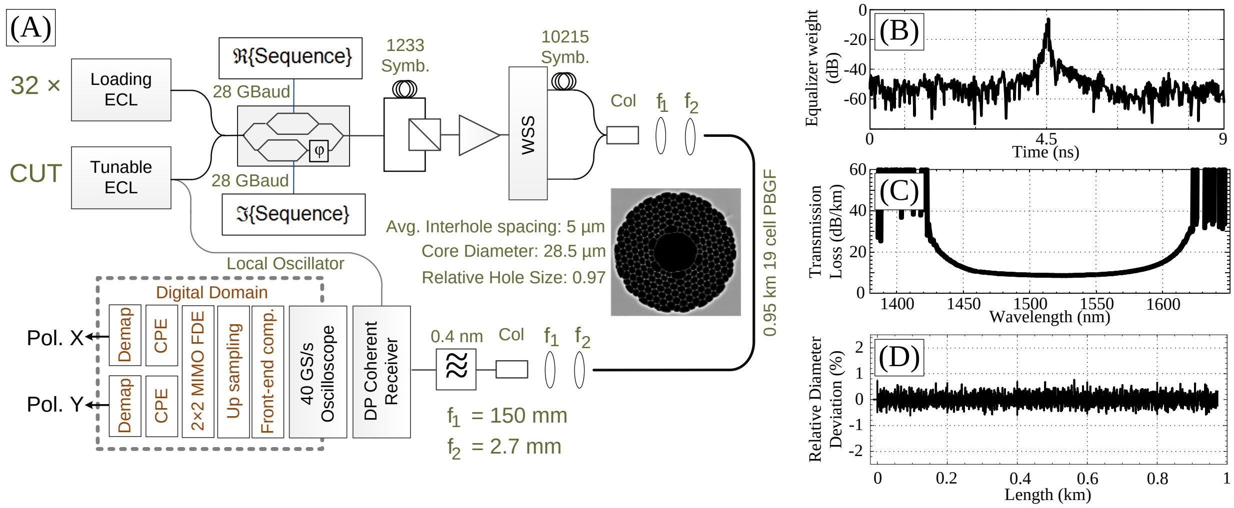

Fig. 1 (A) 0.95 km 19 cell HC-PBGF experimental setup (inset: SEM image of the 19 cell HC-PBGF). (B) The fiber impulse response, and (C) the wavelength transmission window measured over entire length of the HC-PBGF and (D) The relative diameter deviation over 0.95km.

0.95 km long 19 cell photonic bandgap fiber by a collimator (col) and 2 lenses with focal lengths of f_1 = 150 mm and f_2 = 2.7 mm. The inset of Fig. 1a depicts the Scanning Electron Microscope (SEM) image of the used HC-PBGF, which has a 19 cell core structure with a diameter of 28.5 µm. The HC-PBGF is optimized for surface mode suppression [3], and has a microstructured cladding designed for operation around 1.5 µm. The average interhole spacing is around 5 µm, and the relative hole size is approximately 0.97. The fiber attenuation, measured over the entire length, is shown in Fig. 1c. From this figure. The minimum loss of 8 dB/km is at ~1.51 µm and the 3dB bandwidth corresponds to the widest bandwidth low loss HC-PBGF reported [3]. The average attenuation in the C band is 9 dB/km. At the receiver side, a reciprocal setup of the transmitter launcher is used. Then, a DP coherent receiver is employed. A 4-port 40GS/s real-time oscilloscope is used as 4 synchronized analog to digital converters (ADCs). In the digital domain, first the front-end is compensated before up sampling to 56 GS/s. Then, a 2×2 multiple-input multiple-output FDE is used. The FDE uses the overlap-save method with 50% overlap [7]. The FFT size is 128, and the step size is $3\cdot10^{-4}$. To minimize the convergence time, an adaptive step size was used [8]. Previously, it was noted that the impulse response of 19 cell HC-PBGFs is longer for solid core silica fibers [5]. However, from the impulse response shown in Fig. 1b, excellent single mode performance can be seen, as no other impulses from other modes are present. As the complexity of FDE scales logarithmically with the impulse response length, the complexity scaling is minimized. This allows for low-complexity DSP to enable longer transmission over novel HC-PBGFs. The FDE weights are heuristically adapted using the least mean squares (LMS) algorithm during initial training sequences, and decision-directed LMS (DD-LMS) during data transmission. Although the transmitter laser and local oscillator are coming from the same laser source, a carrier phase estimation (CPE) algorithm is still required to compensate the phase difference. Per transmitted polarization channel, a concatenated phase detector and digital phase locked loop is used as CPE stage [9]. After the CPE stage, the gray-coded constellations are demapped, and the bit error rate (BER) is estimated. The BER is estimated over 2×560,000 symbols per polarization, which results in averaging over 4.48 and 5.6 million bits for 16 and 32 QAM, respectively.

3. Results

Fig. 2a. shows the single channel back-to-back (BTB) and 0.95 km 19c HC-PBGF transmission performance of 16 and 32QAM. At the soft-decision (SD) forward error correcting limit (FEC), for 16QAM there is no penalty between BTB and after transmission. However, when considering the hard-decision (HD) FEC limit, a 0.5 dB OSNR penalty is noticed. As the 32QAM is a denser constellation, the OSNR requirements are more stringent. At the SD-FEC limit, a 1.5 dB OSNR penalty is noticed after transmission with respect to BTB performance.

Fig. 2b shows the successful demonstration of the 100GHz ITU-grid 32-channel experiment for both 16 and 32 QAM. The successful transmission of the 32QAM constellation uses 20% SD-FEC, and 16QAM only uses 7% HD-FEC. In this work, we aim for the maximum capacity the fiber can deliver. Obviously, reducing the number of constellation points will improve the BER performance, and hence reduces the required FEC overhead. The 32 channel system BER performance for both 16 and 32QAM is approximately an order of magnitude higher than the single channel performance, which is depicted in Fig 2a.

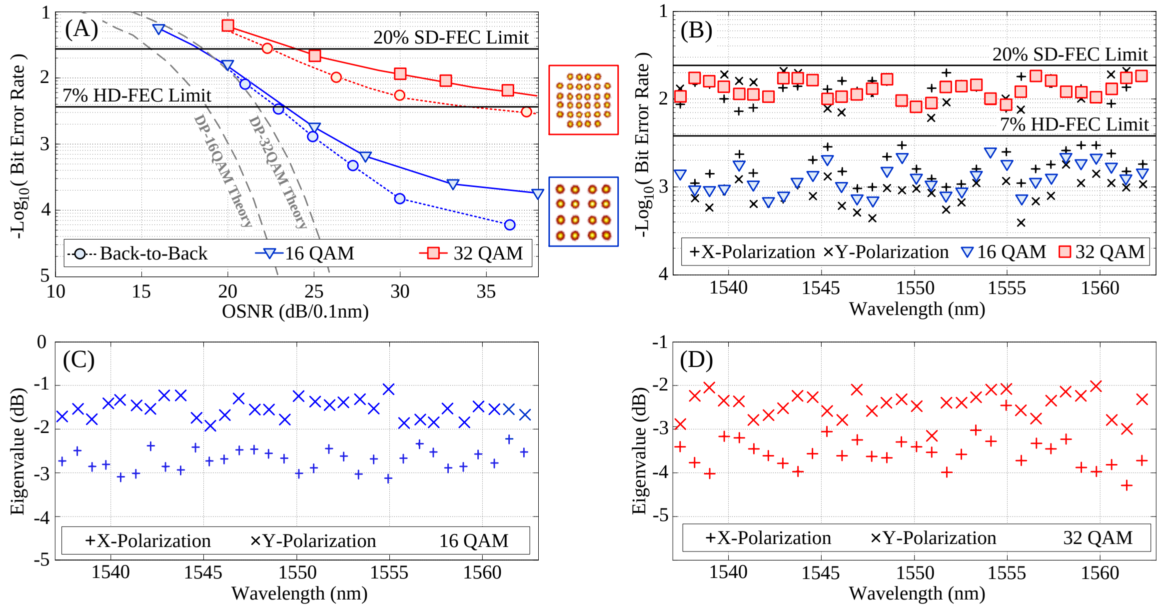

Fig. 2 (A) Single channel OSNR performance for both transmitted constellations. (B) 32 channel experiment BER results. Eigenvalues for polarization dependent loss analysis for (C) 16 QAM, and (D) 32 QAM.

In addition to the 32 channel BER performance, the polarization dependent loss (PDL) is investigated. First, for each capture eigenvalue decomposition on the channel state information is performed [10]. This results in two eigenvalues representing each polarization per analysis at each wavelength, as depicted (in dB) in Fig. 2c and Fig. 2d. for 16 and 32 QAM, respectively. The difference between the two eigenvalues is the PDL. Ultimately, a low PDL fiber is desired for longer distance transmission. However, the PDL indicates the potential transmission capacity of the fiber [11]. Averaging the PDL over the transmitted wavelength span for both transmitted constellations, the average measured PDL is approximately 1.1 dB. The origin of PDL is still under investigation, however, modeling indicates that it is not intrinsic to the fiber but can be attributed to small-scale asymmetries (Fig. 1d) of the HC-PBGF [12]. Through fabrication improvements, these effects can be eliminated.

4. Conclusions

Taking advantage of the improved HC-PBGF drawing process, we report on longer hollow-core photonic bandgap fiber lengths suitable for high data rate coherent transmission. We have shown the successful transmission of 32 wavelength channels on a 100 GHz ITU grid modulated by a 28GBaud gray-coded DP-32QAM signal over 0.95km of the 19cell HC-PBGF. After transmission, a 2×2 MIMO FDE was used at the receiver. By exploiting the eigenvalue decomposition of the channel state information in the receiver MIMO DSP, the polarization dependent loss performance of the hollow-core photonic bandgap fiber is investigated, finding a value of approximately 1.1 dB over 0.95 km, which may originate from small scale core asymmetries. To the best of our knowledge, this transmission represents the longest coherent transmission distance and highest distance × bandwidth product over a 19 cell HC-PBGF. Whilst more work is required in order to fully assess HC-PBGFs as transmission medium over even longer distances, this work demonstrates that HC-PBGFs can already be relevant to high-capacity data transmission applications.

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5. References

[1] E. Desurvire et al., Comptes Rendus Physique, **12**(4), 387-416 (2011).
[2] M. N. Petrovich et al., *Proc. ECOC*, paper Th.3.A.5 (2012).
[3] F. Poletti et al., Nature Photonics **7**, 279-284 (2013).
[4] N.K. Baddela et al., *Proc. CLEO*, paper CTu2K.3 (2013).
[5] V.A.J.M. Sleiffer et al., *Proc. OFC/NFOEC*, paper OW11.5 (2013).
[6] Y. Jung et al., *Proc. OFC/NFOEC*, PDP5A.3 (2013).
[7] N. Benvenuto and G. Cherubini, *Algorithms for Communications Systems and their Applications* (John Wiley & Sons, 2002).
[8] R.G.H. van Uden et al., *Proc. ECOC*, paper Th.2.C.2 (2013).
[9] R.G.H. van Uden et al., Photonics Technology Letters **25**(14), 1381-1384 (2013).
[10] R.G.H. van Uden et al., *Proc. Sum. Top.*, WC4.2 (2013).
[11] P.J. Winzer and G.J. Foschini, Optics Express **19**(17), 16680-16696 (2011).
[12] F. Poletti et al., Optics Express **13**(22), 9115-9124 (2005).