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0.61 Pb/s S, C, and L-Band Transmission in a 125µm Diameter 4-core Fiber Using a Single Wideband Comb Source

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***Abstract*—We investigate high-throughput, multi-band transmission in a 4-core multi-core fiber (MCF) with the same 125 µm cladding diameter of standard single-mode fiber (SMF). A single wideband comb source is used to transmit up to 561 wavelength channels with 25 GHz spacing over a 120 nm bandwidth in S, C and L bands. We demonstrate a maximum decoded throughput of 610 Tb/s in PDM-256QAM and PDM-64QAM signals over a 54 km fiber, with a per-core average throughput exceeding wideband transmission demonstrations in single-mode fibers and highest single core throughput of 155.1 Tb/s. In addition, we use noise loading measurements to characterize the achievable signal quality across the wideband transmitter. These results show that a single comb source can enable high-spectral efficiency modulation over wide bandwidths and further that low-core count homogeneous MCFs technology can offer the same transmission performance as single-mode fibers without sacrificing mechanical reliability, and still offering the benefits of shared resources and greater efficiency that drives SDM technologies.**

***Index Terms*—Optical Fiber Communication, Multi-core fiber, Space-Division Multiplexing, Optical Comb Source**

I. Introduction

Space-division multiplexing (SDM) is often proposed as a means of increasing the transmission capacity of optical fibers whilst also improving efficiency and reducing costs [1], [2]. Numerous large-scale demonstrations have been reported in single-mode multi-core fibers (MCFs) [3], [4] and multi/few-mode (FM) fibers[5], [6]. Combining FM cores in an MCF has enabled >10 Pb/s transmission, albeit with an enlarged cladding diameter of 267 µm [7] or 312 µm [8]. However, there is still a question regarding the practicality of large cladding diameter SDM fibers, with the mechanical reliability, failure probability, splice loss and the length of fiber that can be drawn from a single pre-form, all strongly dependent on the cladding diameter [9]. This has led to a recent trend of exploring high spatial-density SDM transmission in medium cladding diameter fibers. This includes demonstrations such as 100 km repeated transmission in a 171 µm wide 6-mode, 7-core fiber [10] and 1.2 Pb/s transmission in a 3-mode, 4-core fiber with 160 µm [11]. Furthermore, fibers with standard 125 µm cladding diameters and up to 45 modes have enabled numerous > 100 Tb/s transmission demonstrations [5], [6], [12]–[15] with the largest being 401 Tb/s using 10 modes [12]. Coupled-core fibers have also been shown to offer multiple spatial channels in a standard cladding diameter with improved non-linear tolerance over SMF over long distances [16] and recently demonstrated over a wide-wavelgnth range for the first time [17]

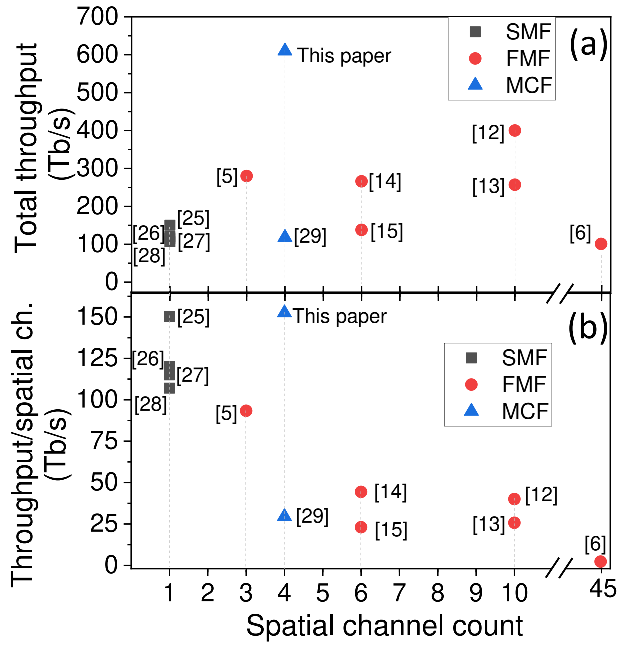

Fig. 1. Transmission demonstrations with net data-rate exceeding 100 Tb/s in 125 µm cladding diameter fibers

For near-term adoption of SDM technology homogeneous single-mode MCFs, compatible with existing SMF infrastructure, are likely to offer the simplest migration path. Such fibers have been shown to support wideband, high spectral-efficiency modulation, without requiring high-order

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multiple input-multiple output (MIMO) based receivers [4], as well as long-haul transmission [18], also with multi-core amplifiers [19]. Without MIMO, spatial sub-channels may be independently, optically routed, allowing MCF use in a wider range of network scenarios. In addition, the uniformity of homogeneous cores allows aggregating wavelengths on multiple cores into spatial super channels (SSCs) enabling both shared hardware and joint processing benefits [20]–[22].

Here, show that such MCF benefits can be obtained even when limited to the diameter of a SMF. We expand on a previous experiment [23], and report an improved transmission experiment with higher order modulation format and increased throughput. We also perform an OSNR characterizing of the wideband comb transmitter. As shown in Fig. 1, which summarizes transmission experiments exceeding 100 Tb/s in 125 µm diameter fibers, we report transmission in a 4-core fiber [24] with per-core throughputs exceeding the highest reported in SMF to date [25]–[28] and exceeding the previous record throughput for a 125 µm diameter MCF [29] by more than 5 times. Wideband transmission is achieved by using a single extended bandwidth frequency comb [30] generated from a seed laser that may also be transmitted across networks through MCF cores for comb regeneration [31]. We report record throughput of any 125 µm diameter fiber with carriers covering a 120 nm bandwidth over S, C and L bands. We transmit up to 561×24.5 GBd, 4-core SSCs in a wavelength range from 1489.65 nm to 1609.82 nm, on a 54 km, 4-core MCF [24]. We use a combination of polarization-division multiplexed (PDM)-256 quadrature amplitude modulation (QAM) and lower order QAM formats to achieve a maximum decoded throughput of 610.4 Tb/s, with an average per-core throughput of 152.5 Tb/s and maximum per-core throughput of 155.1 Tb/s. This experiment shows that homogeneous MCFs can provide the reliability of smaller diameter fibers [9] together with the benefits of SDM hardware and resource sharing whilst still supporting high-capacity transmission.

II. Description of Experiment

Fig. 2 shows the primary transmission experiment set-up. A wideband comb-source [4], [30] generated 25 GHz spaced carriers over 120 nm bandwidth with a total output power > 2W and output spectrum shown in Fig. 3(a). The comb output was first split in a high-power tolerant polarization-maintaining coupler to generate a sliding test-channel band for high quality modulation and a non-measurement band covering the remainder of the utilised spectrum. For the test-band, different configurations were used depending on the test-channel wavelength. A wavelength-division multiplexing (WDM) coupler was used to separate S-band wavelengths from those in C- and L-band. On both coupler outputs, a tunable band-pass filter (TBPF) was used to select channels for modulation. A three-channel test-band was used for the C/L band measurement to minimise inaccurate automated power adjustments resulting from power variations between neighbouring channels around the comb seed. A 5-channel test-band was used for S-band channels. C- and L-band paths were separated in a C/L WDM coupler before being amplified to 27dBm in a C- or L-band EDFA. S-band test-channels were amplified in a semiconductor optical amplifier (SOA) with gain peak at 1490nm and >70nm bandwidth. The test-channel carriers were then divided into odd and even channels by the appropriate interleaver (INT) to allow separate modulation of neighbouring channels in two dual-parallel Mach-Zehnder modulators (DP-IQ) driven by four arbitrary waveform generators (AWGs) operating at 49 GS/s. These produced 24.5 GBd, root-raised cosine shaped, polarisation division multiplexed PDM-QAM signals with a roll-off of 0.01 based on pseudo-random binary sequences. Additionally linear pre-equalization of the signal was used to compensate for the AWG frequency limitations. C- and L-band channels were modulated with PDM-256QAM signals with S-band channels first measured with PDM-16QAM modulation before being measured with PDM64-QAM modulation after optimisation. The odd and even channels were then combined, after decorrelation with different optical delays from patch-cords and components of 150 ns, and further amplified in either an EDFA or Thulium doped fiber amplifier (TDFA). The TDFAs had a total output power > 20 dBm and noise figure below 7 dB specified over a wider wavelength range (1460 nm to 1520nm) than utilised here.

The non-measurement band was also split between C/L and S-band paths, with each containing a single-polarization (SP)-IQ modulator with a polarization-multiplexing stage before amplification in C/L EDFA or TDFA stage. In C- and L-band, optical processors (OPs) were used to both flatten the comb spectrum and carve a notch to accommodate the test-band before recombination. In the absence of an S-band OP, best effort flattening was achieved by tuning the gain profile of the

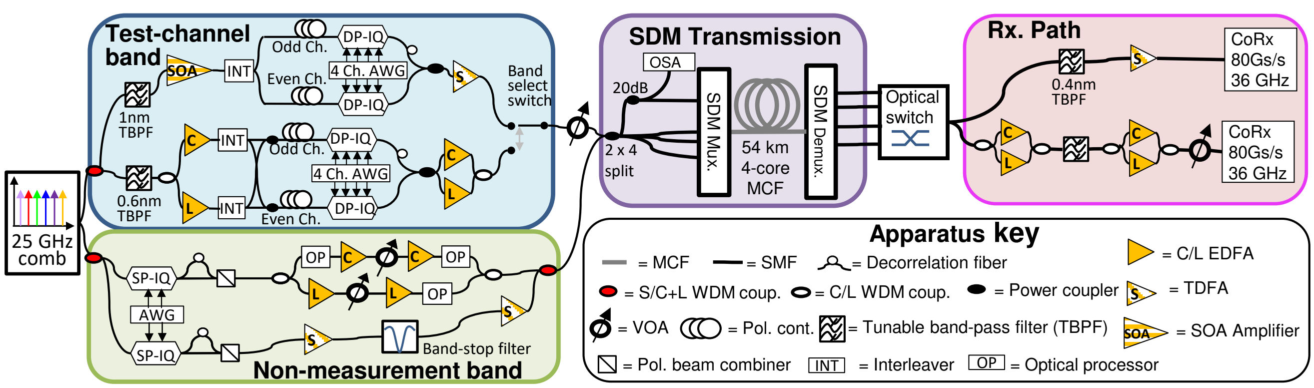

Fig. 2. Experimental set-up for S. C and L-band transmission in 4-core 125 μ m cladding diameter MCF with wideband comb transmitter

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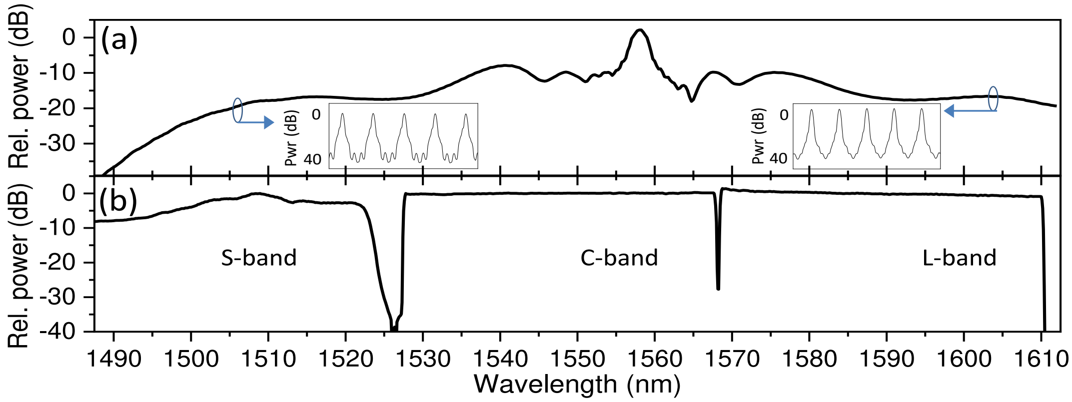

Fig. 3. (a) Unflattened comb output with insets of comb lines and (b) Transmission spectrum of S, C and L-band signal

SOA and an additional TDFA. A notch was carved in the dummy S-band using a tunable band-stop-filter. The bands were then recombined with WDM couplers before being merged with the test band in a power coupler with a switch used to select the appropriate test-band input for the measurement.

For SDM transmission the combined multi-band signal, shown in Fig. 3(b), was divided in a 2 x 4 power splitter to produce 4 spatial sub-channel signals with optical patch-cords of length 2 m, 4m and 6m used for temporal de-correlation of spatial channels. The transmission fiber was a homogeneous 4-core SM-MCF described in [24]. The loss of the fiber and multiplexers varied from 12.3 dB to 13.8 dB and each core had a mode-field diameter at 1310 nm between 8.4μm and 8.6 μm, similar to SMF. The crosstalk between cores was < -60 dB/km for the S-band channels and <-45 dB/km in the L-band. The total fiber launch power was around 23 dBm with 19 dBm each for combined C- and L-band channels and 17 dBm for all S-band channels.

The C/L receiver path consisted of amplification stages on either side of a 0.4 nm TBPF centered on the test-channel. A VOA was used for power adjustment at the input of the coherent receiver (CoRx). The S-band receiver used only a single TDFA and TBPF. An external cavity laser with a nominal linewidth <100 kHz was used as a local oscillator (LO). The signals were digitized by a real-time oscilloscope at 80 GS/s and the traces stored for offline processing. The DSP consisted of stages for resampling to 2 samples per symbol and normalization, followed by a time-domain 2 x 2 MIMO equalizer using 33-taps for all channels. The taps were initially updated using a data-aided least-mean squares algorithm before switching to a decision directed algorithm after convergence and carrier recovery was performed within the equalizer loop. The throughput of each wavelength channel was independently assessed using LDPC codes from the DVB-S2 standard and described in detail in [5]. To allow for rate-flexibility, LDPC code-rate puncturing with a rate-granularity of 0.01 was implemented to achieve a bit error rate (BER) below 2.18×10^{-5} [32]. Below this BER, it was assumed that a 2.8% overhead outer hard-decision code, could remove any remaining bit errors. Iterative decoding was performed using at least 100 code words per channel with the highest code rate meeting this target BER including an additional 10% margin. Measurements were performed on all space and wavelength channels in sequence. After tuning of each wavelength channel, an optical switch used to direct the output of each of the 4 fiber cores to the appropriate receiver path and digital traces of each core signals were saved in turn. Signal quality measurements were based on three 10 μs traces.

III. Wideband Transmission Characterisation

To study the transmission characteristics of the wideband transmission systems a simplified set-up, shown in Fig. 4, was used. The power of amplified spontaneous emission (ASE) noise from filtered EDFA or TDFA stages was controlled with VOAs and combined with received signals to perform signal quality measurements as a function of the received optical signal-to-noise ratio (OSNR). Single channel measurements were performed on channels with 250 GHz spacing (every 10 channels of those used in transmission experiment) across the S, C and L bands. The transmitter was largely similar to that described in the previous section, but with the same modulator operating with only a single wavelength input. Measurements were taken with PDM-QPSK, PDM-16QAM and PDM-64QAM modulation, but the highest achievable OSNR with PDM-256QAM modulation lead to error floors above the target BER threshold for most channels prohibiting similar measurements. Fig. 5 is a summary of the results, and for each wavelength channel shows the required OSNR (R-OSNR) for a BER of 2.7 x 10^{-2}, often used a guideline BER threshold for use of soft-decision forward error-correction (FEC).

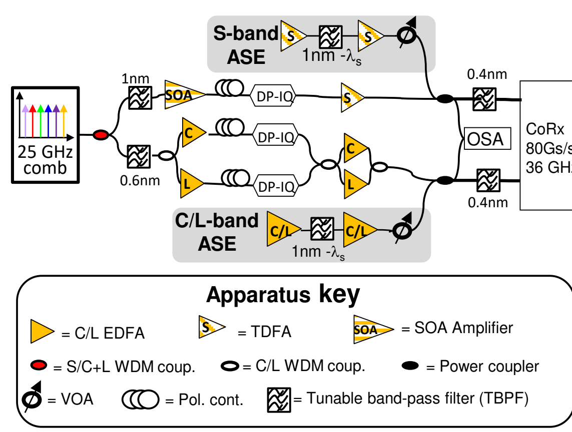

Fig. 4. Experimental set-up for noise-loading BER measurements to characterize wideband transmitter

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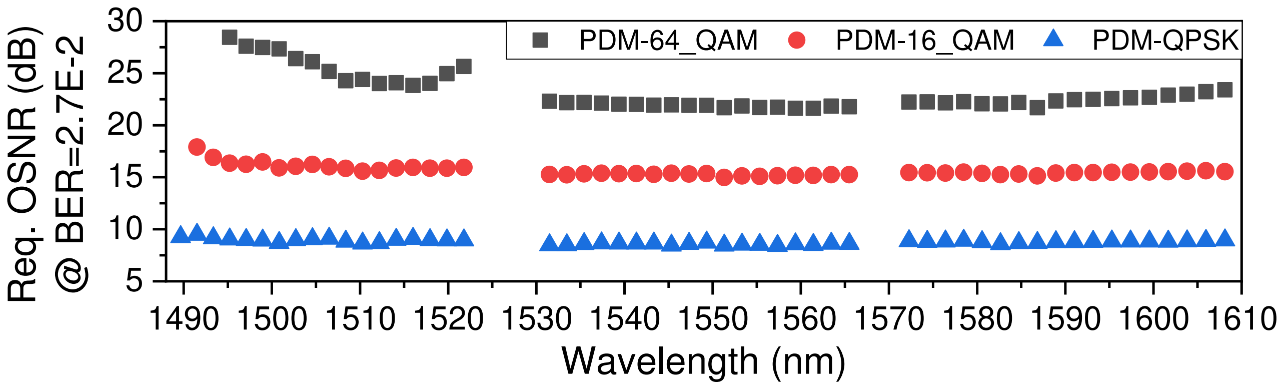

Fig. 5. Comb Tx characterization - Required OSNR (BER = 2.7 x 10^{-2}) vs. wavelength for PD- 64QAM, PDM16QAM an PDM-QPSK modulation

Fig. 5 shows that increasing the order of modulation of the QAM formats reveals limitation in the achievable OSNR of the comb transmitter for wavelengths furthest from the 1558 nm seed wavelength. With PDM-QPSK modulation, the R-OSNR is broadly constant around 8 dB. For PDM-16QAM, the same trend is observed for the majority of channels with R-OSNR ≈ 15 dB, but slowly increasing to almost 18 dB for short wavelength S-band channels below 1500nm. Moving to PDM-64QAM modulation further reveals the wavelength dependence of comb line SNR. The lowest R-OSNR of around 22 dB is observed in the high-C-band around the comb seed and slowly increasing towards the highest wavelength L-band channels. In the S-band, channels around 1510 nm have a similar R-OSNR as the longest L-band channels a similar distance from the comb seed with the R-OSNR then increasing to over 28dB for the shortest wavelength measurable channels as the SNR reduces with similar shape to the comb line power shown in Fig. 3(a). The R-OSNR of higher wavelength S-band channels also increases due to the lower gain and higher noise figure of the TDFAs at wavelengths on the edge of their gain-bandwidth.

IV. Transmission Results

This section describes transmission results achieved with the set-up described in section II. The first transmission experiment, described in [23], used PDM-256QAM modulation for C and L-band channels and PDM-16QAM modulation for S-band channels due to difficulty in successful reception of higher order modulation for short wavelength S-band channels. Fig. 6(a), shows the average and per-spatial sub-channel (SSubCh.) SNR estimated form the received data in this experiment and shows that the received SNR should have allowed transmission of higher order formats and it was subsequently determined that a key issue was the auto-bias circuitry (ABC) of the modulator. Possibly resulting from an impaired response of the ABC photo-diodes at S-band wavelengths, it was observed that sub-optimal bias was achieved with the ABC and successful transmission of PDM-64QAM settings could be achieved by adopting manual bias tuning for the lower S-band channels. Furthermore, the WDM couplers used to combine S-band channels with the C/L-band channel in [23], was observed to transition between the reflect and pass ports just beyond 1520nm, thus blocking some channels still within the TDFA gain bandwidth. By selecting couplers with slightly higher transition wavelength, additional channels in the high S-band could be received. Fig. 6(b) shows the measured throughput of PDM-16QAM S-band channels with decoded throughput of the combined 4-core SSC ranging from 0.45 Tb/s to 0.75 Tb/s, lower than what could be expected with PDM-64QAM in the same SNR range, showing that the overall throughput could be improved by adopting higher order modulation.

Fig. 7 shows a summary of the improved transmission experiment utilizing PDM-64QAM modulation for all S-band channels and PDM-256 QAM for C- and L-band channels. It is apparent that it is not possible to recover the shortest wavelength S-band channels with higher order modulation although additional channels above 1520nm were possible after replacing the WDM coupler. Fig. 7(a) again shows the signal-to-noise ratio (SNR) estimated from the received data as a function of wavelength for each core (spatial sub-channel) and the average. The received SNRs of received channels in the full WDM transmission show a similar picture to the single channel characterization described in the previous section. On the whole, the achievable OSNR of a given wavelength is determined by the distance from the comb-seed wavelength with the exception of spectral areas, such as the higher wavelength S-band channels, where the achievable SNR after transmission is additionally limited by reduced gain and higher NF at edges of the amplifier pass-band.

Fig. 7(b) shows the combined decoded throughput of each SSC together with the data-rate estimated from the generalized

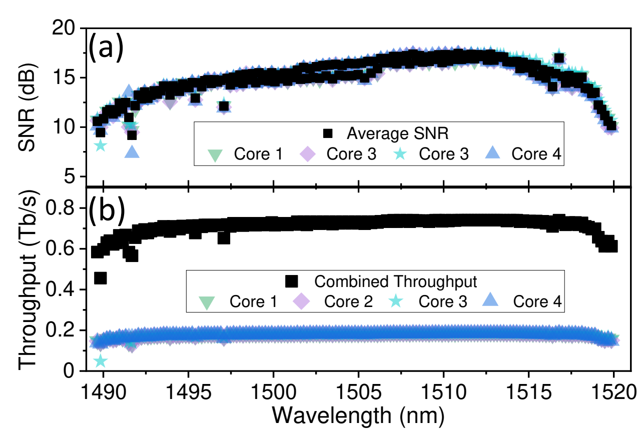

Fig. 6. (a) Per-SSubCh (core) and average SNR, and, (b) Per-SSubCh and combined throughput for PDM-16QAM S-band channels

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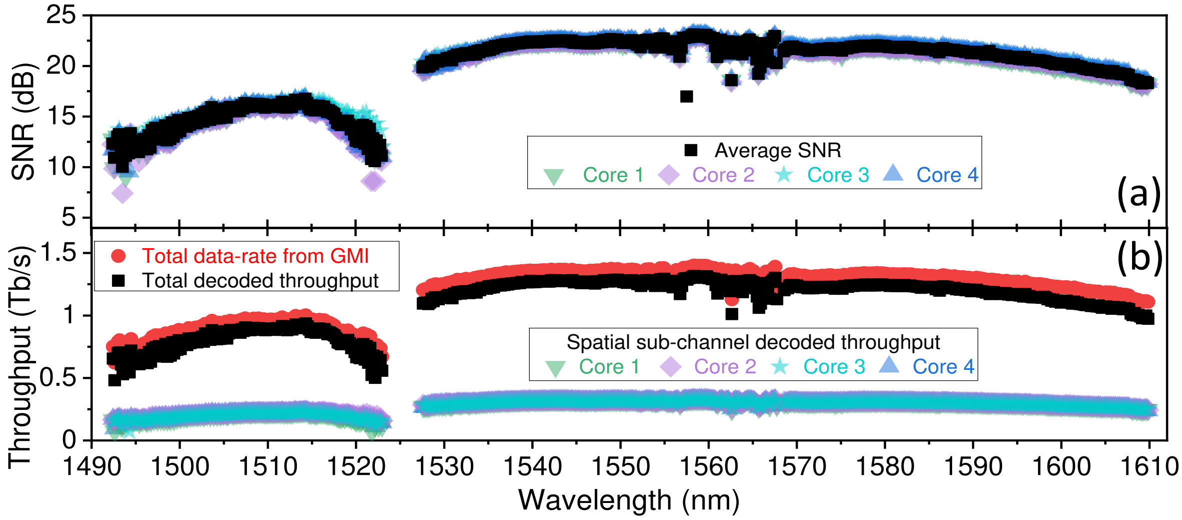

Fig. 7. For all received wavelength channels (a) average and per-spatial sub-channel signal-to-noise ratio estimated from data and (b) combined spatial super-channel and per- sub-channel decoded throughput and total throughput estimated from GMI

mutual information (GMI). The decoded throughput of each individual core (spatial sub-channel/SSubCh.) is shown together with the combined SSC throughput, whilst for clarity only the combined date rate estimated from the GMI is shown. The decoded throughput of C and L-band channels ranged between 0.9 and 1.4 Tb/s per SSC, reducing to a range of 0.45 to almost 1 Tb/s for the PDM-64QAM, S-band channels. The GMI estimated data-rate is on average 8% higher than the decoded net data-rate, showing the potential for higher throughput with more effective coding. The S-band per-channel throughput peaks at around 1514 nm with longer wavelengths impaired by the TDFA gain profile. Towards lower wavelengths the reduced SNR of comb lines for lower wavelength channels, evident from Fig. 5, reduces the achievable throughput. Furthermore, evidence of additional phase noise was observed on channels far from the comb seed and an additional loss penalty can be expected at the shortest wavelengths since the majority of utilized components are designed for C-band operation. In particular, the interleaver provided less effective suppression of neighboring channels at shorter wavelengths and the fiber loss was increased by 2dB for the lowest S-band channels compared to 1550nm.

The C and L band channels show relatively uniform performance across more than 80 nm of bandwidth. Some variation in performance is evident around the comb seed wavelength where some OSNR variation and differences in the power of neighboring channels is observed, resulting in different WDM penalties and performance variation on some channels. As in previous experiments [4], signal quality reduces for longer L-band wavelengths which is believed to derive from additional phase noise away from the comb seed and gain and noise figure profile of the L-band EDFAs.

A small variation of 2.4 % in total throughput put could be observed attributed to variation in loss between fiber cores, multiplexers, splitter and the optical switch. The lowest loss core had a throughput of 155.1 Tb/s with throughputs of 152.5, 151.4 and 151.2 Tb/s in the remaining 3 cores. We note that the total throughput measured here is more than 50% higher than the largest throughput measured in a standard cladding diameter fiber [12] and more than 4-times larger than the record throughput of a single-mode optical fiber [25]. The average per-core throughput of 152.5 Tb/s exceeds the largest reported SMF transmission experiment and is also achieved with almost 10 nm narrower bandwidth [25], showing potential for improved throughput in this system. We note that with an improved comb or adopting alternative transmitter lasers additional data throughput could be obtained by utilizing S-band channels in the region below 1490nm where TDFA bandwidth remains and from extending the high wavelength cut-off to reduce the size of the guard band between S- and C-bands. Further improvement could also be achieved by adopting continuous SOA amplifiers utilized in previous wideband transmission demonstrations [27], [28]. Finally, we note that increased throughput and potentially higher-order modulation, could be achieved with optical components better optimized for S-band transmission, thus highlighting the challenges of adopting new optical fiber transmission windows.

V. Conclusion

We have investigated wideband transmission over S, C and L bands in a 4-core fiber with standard cladding diameter using a single wideband comb transmitter with > 120nm bandwidth. Noise-loading measurements were first used to characterise the multi-band comb transmitter before performing a transmission demonstration using 561 x 24.5 GBd channels with PDM-256QAM and PDM-64QAM modulation across the 3 bands. We report a net data-rate after decoding of over 610 Tb/s in the 125 um cladding-diameter fiber, with the average per-core data-rate of 152.5 Tb/s exceeding the largest yet measured in multi-band transmission demonstrations using single-mode fibers. These results show the potential of for ultra-high throughput transmission systems from a single optical comb. Further, they demonstrate that low-core count homogeneous MCFs technology can multiply the achievable throughput of SMFs without sacrificing the mechanical reliability and still offering benefits of shared resources and greater efficiency that drives SDM technologies.

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