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

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Abstract: We demonstrate 596.4 Tb/s over a standard cladding diameter fiber with 4 single-mode cores, using a single wideband optical comb source to provide 25 GHz spaced carriers over 120 nm range across S, C and L bands.

1. Introduction

Space-division multiplexing (SDM) is often proposed as a means of increasing optical fibers transmission capacity whilst also improving efficiency and reducing costs. Numerous large-scale demonstrations have been reported in multi-core fibers (MCFs) and few-mode (FM) fibers[1] with a 19-core FM enabling record >10 Pb/s transmission [2], albeit with an enlarged cladding diameter of 267 µm. However, the mechanical reliability, failure probability, splice loss and the length of fiber that can be drawn from a single pre-form, are all strongly dependent on the cladding diameter [3]. This has led to a recent trend of exploring high spatial-density SDM transmission in medium cladding diameter fibers [4, 5] and exploration of standard 125 µm diameter fibers with up to 10-modes [6] or coupled-cores which also offer improved non-linear tolerance over SMF over long distances [7]. For near-term adoption of SDM technology homogeneous single-mode MCFs, compatible with existing SMF infrastructure, are likely to offer the simplest migration path and have been shown to support wideband, high spectral-efficiency modulation, without multiple input-multiple output (MIMO) based receivers [8], and long-haul transmission [9]. Without the need for MIMO, spatial sub-channels may be optically routed independently, 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 [10].

Here, we show that MCFs limited to the diameter of SMF can achieve per-core throughputs on a par with the highest reported in SMF [11–13]. Wideband transmission is achieved by using a single extended bandwidth frequency comb [14] generated from a seed laser that may also be transmitted across networks through MCF cores [15]. 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 559×24.5 GBd, 4-core SSCs, from 1489.4 nm to 1609.82 nm, on a 54 km, 4-core MCF [16]. We use polarization-multiplexed (PM)-256 quadrature amplitude modulation (QAM) for C and L-band channels and PM-16QAM for S-band channels to achieve a total decoded throughput of 596.4 Tb/s, with a per-core throughput of 149.1 Tb/s, within 1% of the highest recorded in SMF to date [11]. This experiment shows that homogeneous MCFs can provide the reliability of smaller diameter fibers [3] together with the benefits of SDM hardware and resource sharing whilst still supporting high-capacity transmission.

2. Experimental Set-up

Fig. 1 shows the measurement set-up. A wideband comb-source [8, 14] generated 25 GHz spaced carriers over 120 nm bandwidth with a total output power > 2W and output spectrum shown in Fig. 2. The comb output was first split into a sliding test-channel band for high quality modulation and a non-measurement band of dummy-channels covering the remainder of the utilized spectrum. A wavelength-division multiplexing (WDM) coupler was used to separate S-band wavelengths from those in C- and L-band. On both coupler outputs, tunable band-pass filters

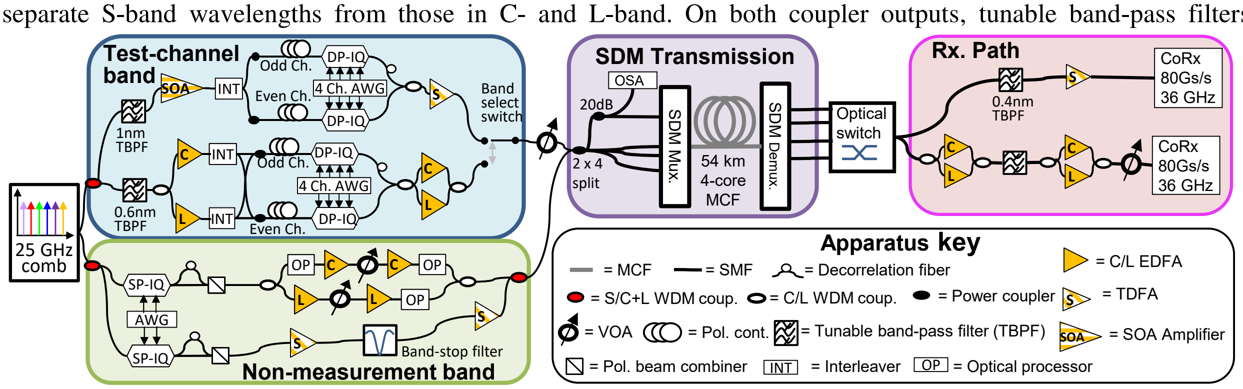

Fig. 1. Experimental set-up for wideband 4-core fiber transmission

(TBPF) were used to select channels for modulation. A 5-channel test-band was used for S-band channels but reduced to three-channels in C/L band where power variation around the comb seed affected power measurements used in automation. A C/L WDM coupler then directed the test channels to the appropriate 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 divided into odd/even channels in optical interleavers (INT) to allow independent modulation of neighbor 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 signals with a roll-off of 0.01 based on 2^{16}-1 bit pseudo-random binary sequences. C- and L-band channels were modulated with PM-256QAM with PM-16QAM used for S-band channels. The odd and even channels were then combined and 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 for transmission band of 1460 nm to 1520nm.

The WDM dummy channels were also split between C/L and S-band paths, with each containing a single-polarization (SP)-IQ modulator with a PM stage before amplification in C/L EDFA or TDFA. 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 amplifier gain profiles with the notch created by a tunable band-stop-filter. The S, C and L bands were then recombined with WDM couplers to give the spectrum shown in Fig. 2, before the test-band was added in a power coupler. A 2 x 4 power splitter with different optical path lengths was used to generate de-correlated signals for each of the 4 fiber cores of the 54km homogeneous 4-core SM-MCF [16]. Each core had a mode-field diameter at 1310 nm between 8.4 and 8.6 µm with combined fiber and multiplexers loss ranging from 12.3 dB to 13.8 dB. The inter-core crosstalk 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-bands and 16 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 with only a single TDFA used for S-band reception. A VOA was used for power adjustment at the input of the coherent receiver (CoRx) with <100 kHz nominal linewidth local oscillator (LO). The signals were acquired by a real-time oscilloscope at 80 GS/s that stored traces for offline processing, which 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 C-band signals and 81 taps for L-band channels. Those were initially updated using a data-aided least-mean squares algorithm, switching to a decision directed algorithm after convergence. 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 [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} [17]. 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.

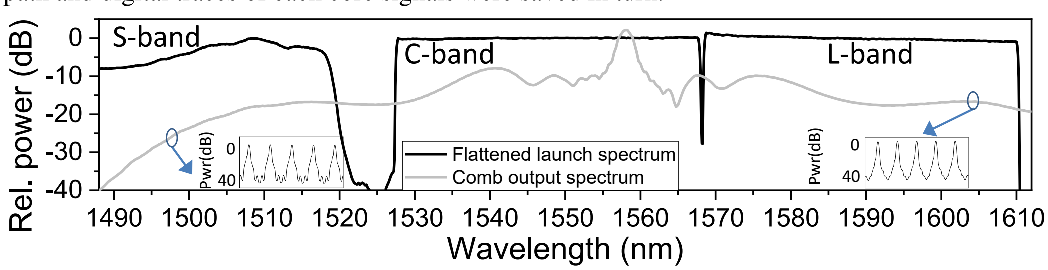

Fig. 2 Unflattened comb output and launched S, C and L-band spectrum with insets of comb lines

3. Results

Fig. 3. shows a summary of the experimental results with the average signal-to-noise ratio (SNR) of each wavelength channel estimated from the received data on the right axis. The left axis shows both the combined decoded throughput of each SSC together with the date-rate estimated from the generalized mutual information (GMI). The throughput of C and L-band channels ranged from 0.9 to 1.4 Tb/s per SSC, reducing to 0.45 to 0.8 Tb/s for the S-band channels with lower order modulation. The GMI estimated data-rate is on average 8% higher for the PDM-256QAM C + L band channels and approximately 6% higher for PDM-16QAM S-band channels, showing the potential for higher throughput with more effective coding. The S-band performance is highest around 1512 nm. At longer wavelengths, the gain profile of the TDFAs dips before the pass-band of the S-band WDM couplers cause a sharp drop in SNR. Towards lower wavelengths the SNR and achievable throughput drops steadily as a result of several factors. At the edges of the comb, the OSNR of carriers starts to reduce from >45 dB at the comb seed with a

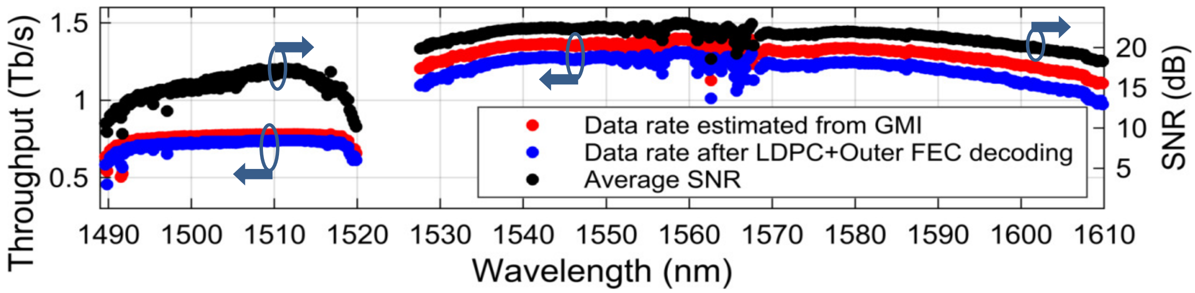

Fig. 3 Combined 4-core throughput estimated from GMI and after LDPC decoding and outer FEC (left axis) and measured average SNR (right axis) for PDM-256QAM C + L band channels and PDM-16QAM S-band channels

trend similar to the power curve in Fig. 2. Similarly, evidence of additional phase noise is observed on constellation plots of channels away from the comb seed. Additionally, the majority of utilized components are designed for C-band operation resulting in higher losses and lower SNR at shorter wavelengths. In particular, the C-band optimized interleaver provided less effective suppression of neighboring channels at shorter wavelengths and the total fiber and component loss was increased by 2 dB 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 OSNR and power variation between neighboring channels leads to performance variation on some channels. The signal quality also reduced slightly for longer L-band wavelengths arising from additional phase noise and the gain and noise figure profile of the L-band EDFAs.

We note that the total throughput measured here is almost 50% larger than the current standard cladding diameter fiber record recently achieved in a 10-mode fiber and over 4-times larger than the record throughput of a single-mode optical fiber [11]. The average per-core throughput of 149.1 Tb/s was also achieved with almost 10 nm lower bandwidth than [11], showing potential for improved throughput in this system. Additional channels could be also be transmitted by use of wider S-band WDM filter to reduce the size of the guard band between S-band and C+L bands. A smaller guard-band could also be achieved by use of continuous SOA amplifiers utilized in previous wideband transmission demonstrations [13]. Furthermore, the increased throughput from higher-order modulation of S-band channels, could be achieved with optical components better optimized for S-band transmission, thus highlighting the challenges of adopting new optical fiber transmission windows.

4. Conclusions

We have measured over 596 Tb/s throughput in a standard cladding-diameter fiber with 4 single-mode cores and achieved an average per-core data-rate within 1% of the highest achieved in single mode-fibers. We transmitted 559 x 24.5 GBd channels over a 120 nm bandwidth with PDM-256QAM modulation and PDM-16QAM modulation with all carriers generate from a single wideband optical comb source. These results show that low-core count homogeneous MCFs technology can offer the same transmission performance as single-mode fibers without sacrificing the mechanical reliability of standard cladding diameter fibers, whilst still offering benefits of shared resources and greater efficiency that drives SDM technologies.

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