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Abstract: We describe experiments combining high core-count, homogeneous single-mode multi-core fibers with a wideband comb for high-capacity transmission without high-order MIMO reception and demonstrate wideband transmission with coded modulation up to 12,300 km.
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1. Introduction

Space-division-multiplexing (SDM) technologies and networking have been widely proposed as cost-effective solutions to increase the transmission capacity in a single fiber by utilizing multiple cores or spatial-modes [1, 2]. Homogeneous, single-mode (HSM)-multi-core fibers (MCFs) offer perhaps the simplest migration path for adoption of high-capacity SDM technology in the near term. Such fibers have been shown to support high spectral efficiency (SE) modulation formats without the complexity of high-order multiple input-multiple output (MIMO) based receivers [3]. They have been used in long-haul transmission, access, data-center and networking demonstrations, may be fabricated with low SDM crosstalk (XT) [4] and the relative uniformity of cores supports spatial super channels (SSCs) for shared transmitter hardware, digital signal processing (DSP) resources and simplified switching [5]. The similar propagation characteristics between cores also support combined multi-dimensional modulation across sub-channel of the SSC, as shown in Fig. 1, and may be further exploited by pilot-tone transmission [5].

However, compared to few-mode multi-core fibers, which have been fabricated with over 100 spatial channels [6, 7], HSM-MCFs are likely to be limited to 20 or 30 cores. Thus, full utilization of the wavelength domain becomes crucial. Hence, covering the C and L band and beyond becomes vital if Pb/s transmission is to be achieved in single-mode MCFs. For maximum SE with channels packed tightly together, the ability of optical comb sources [8] to maintain fixed channel spacing is particularly attractive for wideband systems, as is the potential inventory savings for systems comprising hundreds of channels. Furthermore, the coherency between lines offers potential for compensation of non-linear impairments and additional DSP savings [9]. In this paper, we describe SDM and long-distance transmission experiments and highlight the potential of combining SDM and comb technologies for future high-capacity transmission systems.

2. Experimental Description

Fig. 2 shows the experimental set-ups used in the measurements. Fig. 2 (a) shows the comb transmitter, which uses 3 modulators to modulate over 400 carriers simultaneously. The frequency comb source, custom designed by RAM Photonics, consists of a 1559 nm narrow linewidth (5 kHz) seed laser, modulated with a low noise 25 GHz oscillator, resulting in a 25 GHz spaced comb, which was spectrally broadened in a dispersion engineered fiber mixer [8] for a transmission bandwidth > 10 THz. The total output power was 29 dBm (≈1 dBm/line) and the measured optical signal-to-noise ratio (OSNR) was > 45 dB at 1535 nm and > 47 dB at 1554 nm. In the absence of an individual transceiver for each comb line, the comb output was split into a test band and a dummy channel band using a 3-dB coupler and a tunable band-pass filter (TBPF). The test band consisted of 5 channels over which high OSNR could be maintained. Even and odd channels of the test band were split using interleavers and modulated using 2 dual parallel Mach-Zehnder (DP-QAM) modulators driven by 4 arbitrary-waveform generators (AWG). Each AWG had an analogue bandwidth of 14 GHz and used 49 GS/s sampling rate to generate pre-equalized quadrature-amplitude modulation (QAM) signals at 24.5 GBd with root-raised cosine pulse shape and a roll-off of 0.01. This yielded a narrow channel separation of less than 255 MHz. The remainder of the comb output was

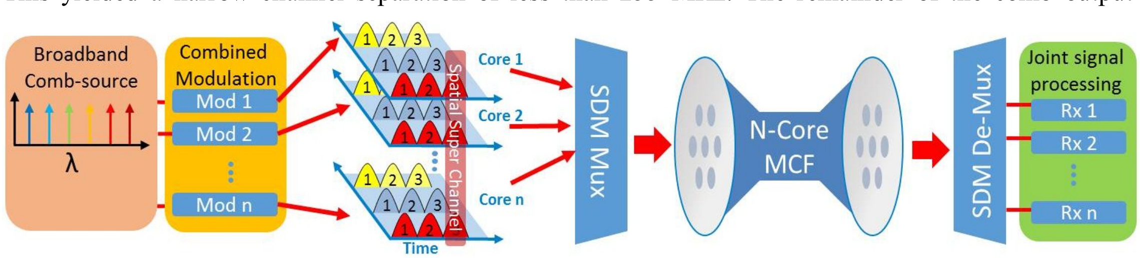

Fig. 1. Schematic of HSM-MCF link with multi-dimensional SSC modulation and joint processing.

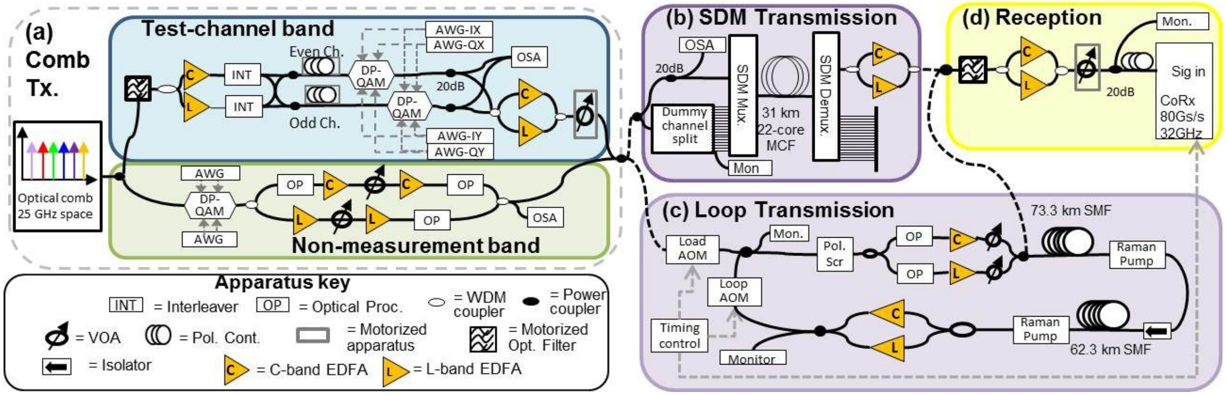

Fig. 2. Experimental set-up:(a) loop transmitter, (b) single-span SDM transmission, (c) recirculating loop transmission and (d) receiver

modulated with the same signal in a DP-QAM modulator. Optical processors (OPs) were used to both flatten the comb spectrum and carve a notch for the channels used in the test band. In both paths, EDFAs and variable optical attenuators (VOAs) were used for power control before recombination and optical spectrum analysers (OSAs) were used for monitoring and feedback for automated control loops. Fig. 2(b) shows the set-up used for single-span SDM transmission. The combined modulated signal was divided between all cores of a 22-core MCF, described in [3], with the signals from each core being received in sequence. 402 comb lines from 1526.63 nm to 1609.41 nm acted as 22-sub-channels of an SSC, each carrying polarization-division multiplexed (PDM) 64QAM signals at 24.5 GBd.

Fig. 2(c) shows the recirculating transmission set-up used to test transmission of a WDM signal of up to 76 nm bandwidth, limited by the passband of the additional optical processors (OPs) needed for gain flattening. Unfortunately, the wide-channel bandwidth meant that to maintain sufficient power/channel through each fiber span, high fiber launch power (21–23 dBm) and high post-span EDFA input power (approx. 10 dBm) were required. The available EDFAs were not optimized for these conditions, so in order to combat the strong resulting gain-tilt, it was necessary to also employ Raman amplification. The combined signal and pump power exceeded the tolerance of the MCF multiplexers, hence the transmission demonstration was performed using standard single-mode fiber (SMF) with dispersion around –20 ps/nm/km. Spans of 72.3 km and 65.3 km were each followed by counter-propagating Raman pumps with additional amplification in separate C and L band EDFAs before fiber transmission and before loop control components including acousto-optic modulators (AOMs), loop synchronized polarization scrambler (Pol. Scr.) and OPs. A single timing control was used for control of AOMs and triggering of receiver oscilloscope.

Fig. 2(d) shows the receiver path. A TBPF was used to select the channel for measurement before amplification and power control at the input to a digital sampling oscilloscope with 32 GHz analogue bandwidth operating at 80 GS/s with offline DSP implemented with MATLAB and C as in [3].

3. Results

Fig. 3 shows the BER summary for the single-span measurements, showing the maximum, minimum and average BER for each 22-core SSC with PDM-64QAM modulation. The spectrum was limited at the edges and around the guard band from EDFA and WDM coupler bandwidths. Higher BERs were observed at higher wavelengths due to the cumulative effect of transmitter phase noise, amplifier noise and the instability of the modulators' auto-bias circuitry. However 399 of the 402 measured SSCs had a BER below a threshold of $2.7\cdot10^{-2}$, assumed for soft-decision FEC [10]. This translated to a raw transmission capacity of 2.58 Pb/s, reducing to 2.15 Pb/s for a 20% coding overhead, which shows the potential of HSM-MCF technology in combination with such a wide-band comb transmitter for Pb/s-class transmission without the requirement for high-order MIMO processing.

Fig. 4(a) shows a BER plot for PDM-16QAM modulation after 1640 km transmission. Even at this moderate

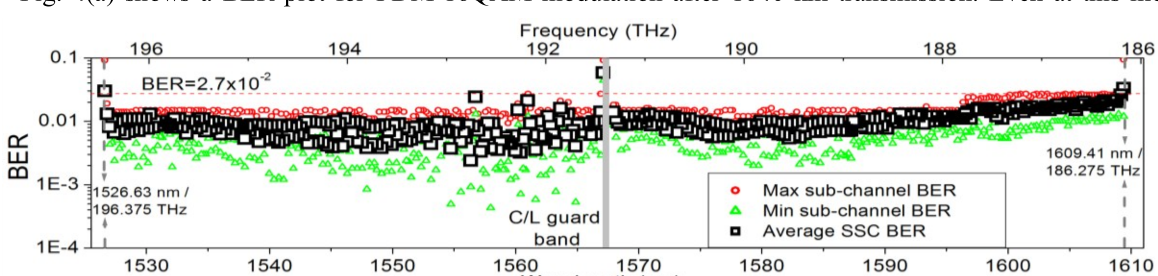

Fig. 3: Max, min and average measured BER of the 22 spatial sub-channels with 24.5 GBd PDM-64QAM modulation of 402 wavelengths between 1526.63 and 1609.41 nm after 31.4 km transmission. 399 SSCs had BERs below the FEC threshold for all 22 sub-channels.

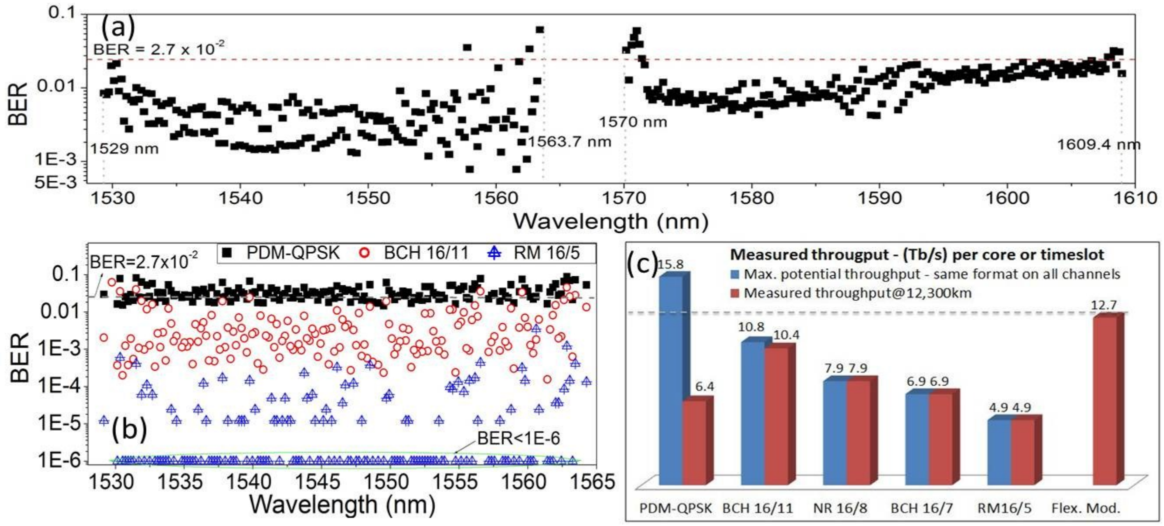

Fig. 4. (a) BER for PDM-16QAM transmission of 358 C- and L-band channels after 1640 km; (b) BER for PDM-QPSK, BCH 16/11 and RM 16/7 for 161 C-band channels after 12,300 km; (c) maximum achievable and measured throughputs for PDM-QPSK, single coded formats and flexible modulation of 161 C-band channels.

transmission distance, the wideband signal shows significant variation in BER over 2 orders of magnitude, showing that the overall capacity-distance product could be improved by equalizing channel performance using flexible choice of modulation format. This idea was investigated using transmission of PDM-QPSK and 4 coded modulation (CM) formats over 12,300 km. The formats were all based on the PDM-QPSK constellation and designed for transmission over 4 cores (16 dimensions) of an MCF, but here they were implemented over 4 consecutive timeslots in the SMF loop. The formats were designed by selecting a subset of the 2^{16} PDM-QPSK points that corresponds to the codewords of certain binary block codes, namely, Bose–Chaudhury–Hocquenghem (BCH) codes [11, Sec. 2.3.1], the nonbinary Nordstrom–Robinson (NR) code [12] and Reed–Muller (RM) codes [11, Sec. 2.3.4]. We refer to these formats by their SEs, which are 11/16 = 0.6875, 8/16 = 0.5, 7/16 = 0.4375 and 5/16 = 0.3125.

Fig. 4(b) shows the measured BER for PDM-QPSK and the BCH 11/16 and RM 5/16 formats. With uncoded PDM-QPSK at the distance of 12,300 km, only 65 of the 161 transmitted channels could be received with a BER under $2.7 \cdot 10^{-2}$. The BCH 11/16 format allowed reception of a further 89 channels below the threshold, with all 161 channels carrying the RM 5/16 format able to be received successfully, many with BER lower than the lowest measureable BER of $1 \cdot 10^{-6}$. The impact of modulation format choice is explored further in Fig. 4(c), which shows, for each format, the maximum achievable throughput if all channels could be received and the throughput for the number of channels successfully received in the experiment. The final column shows the throughput assuming flexible modulation, where for each channel the format with the highest SE or code rate that can be received with BER $< 2.7 \cdot 10^{-2}$ is selected. Fig. 4(c) shows that flexible modulation (12.7 Tb/s) provides 22% larger throughput than the best single format (BCH 11/16, which gives 10.4 Tb/s). Furthermore, flexible modulation offers a greater granularity of achievable throughput that may be tailored to the specific system and distance.

4. Conclusions

We have present experiments demonstrating the potential of a wideband-optical comb and homogeneous-single-mode multi-core fiber (HSM-MCF) for Pb/s class transmission without MIMO processing. We also perform wideband recirculating SMF transmission up to 12,300 km and show that flexible use of multi-dimensional coded modulation, suitable for transmission in spatial-super-channels in HSM-MCFs, can help to optimize throughput.

4. References

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