Pb/s, homogeneous, single-mode, multi-core fiber systems [Invited]

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Pb/s, Homogeneous, Single-mode, Multi-Core Fiber Systems

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Abstract *We discuss multi Pb/s transmission using homogeneous, single-mode, multi-core fibers. We outline the key components of a recent high capacity demonstration, the consequences of fiber properties and the potential for enhanced efficiency from spatial-super-channel transmission.*

Introduction

Space-division multiplexing (SDM) using single mode (SM) and/or few mode (FM) multi-core fibers (MCFs)[1-7] has been widely proposed to address increasing capacity demands by multiplying the number of transmission channels in a fiber for access, data centre and long-haul transmission. As shown in Fig. 1, the per-fiber capacity of MCF transmission has steadily increased in recent years, largely based on homogeneous single-mode MCFs (HSM-MCFs). Early demonstrations in 2011 showed >100 Tb/s with 7-, 12-, and 19-core HSM-MCFs[1-3], increasing to >1 Pb/s in 2012 with a 12-core HSM-MCF[4] and 14-core fiber also containing 2 cores large enough for few-mode (FM) transmission[5]. Recently, transmission capacity demonstrations exceeded 2 Pb/s using a 19-core, 6-mode fiber[6] and a 22-core HSM-MCFs[7].

With over 100 spatial channels per fiber already achieved[6], FM-MCFs have the greatest potential for further capacity increase if the spectral efficiency (SE) and transmission bandwidth can approach that of single mode-transmission. However, this comes at the expense of demanding high-order multiple-input-multiple-output based receivers and additional components to discriminate between modes at the receiver[8]. Alternatively, HSM-MCFs enable a simple migration from single-core fiber systems, with similar receivers allowing high SE modulation formats and wide-band (C+L band) operation[7]. In particular, HSM-MCFs with similar propagation characteristics between cores support the use of spatial super-channels (SSCs) for sharing of transmitter/receiver resources[9], multi-dimensional spatial coding/ modulation[10-13] and self-homodyne detection[14] (SHD). These characteristics potentially allow greater system efficiency beyond just multiplying the number of spatial channels per fiber. Here, we expand on a recent demonstration of ultra-high capacity using HSM-MCFs[7] to include discussion of advanced SDM techniques including SSC coding and SHD, together with the key enabling technologies, their limitations and potential for further improvement.

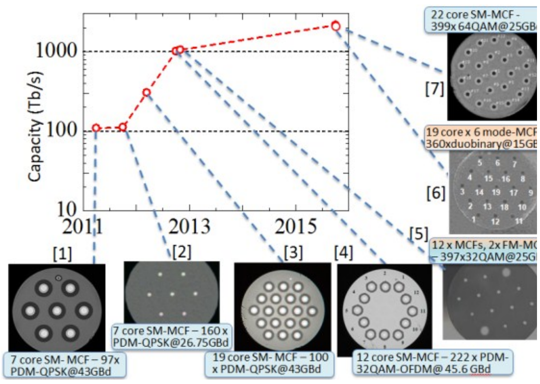

Fig. 1: High-capacity MCF transmission experiments

22-core HSM-MCF Capacity demonstration

The suitability of HSM-MCFs for wideband and high SE modulation was demonstrated by transmission of 22-core SSCs over almost 10THz optical bandwidth enabled by a wideband optical comb[7]. The comb source, custom designed by RAM Photonics, consisted of a 5 kHz seed laser modulated with a low noise 25 GHz oscillator with the resulting 25 GHz spaced comb spectrally broadened in a dispersion engineered fiber mixer[15]. 399 comb lines provided light for 22-sub-channels of a SSC, each modulated with polarization-division-multiplexed (PDM) 64 quadrature amplitude modulation (QAM) at 24.5 GBd. The net data rate was 2.15 Pb/s assuming 20% forward error correction (FEC) overhead at bit-error rate (BER) $<2.7\times10^{-2}$, as summarized in Fig. 2.

The MCF was based on a new 3-ring design with a two-pitch layout and total cladding diameter of 260 μm, as shown in the top-right inset of Fig. 2. The spacing between rings limits the majority of crosstalk (XT) contributions on each core to the 2 adjacent cores in the same ring, evident in Fig. 3, which shows the total measured XT, the XT from 2 neighbouring channels and the average XT contribution of all cores. The total link XT of a 31 km span spliced from 5 separately drawn sub-spans including input/output couplers on the first and last sub-span ranged from -47 dB to -37.5 dB at the comb seed wavelength of 1559 nm. Hence, adopting a

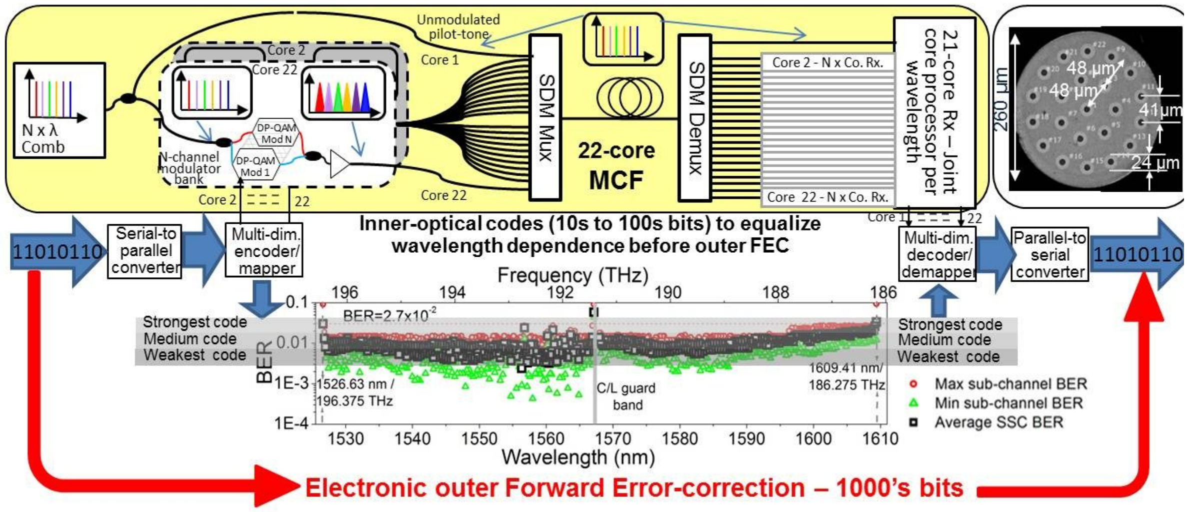

Fig. 2: Schematic of high-capacity MCF link using 22-core fiber (Inset-top right) and BER summary (lower inset) showing the maximum, minimum and average uncoded sub-channel BER

bi-directional transmission strategy[16] is likely to reduce the XT below -40 dB/100 km, where little impact on transmission of up to 64 QAM signals was observed experimentally[17]. However, we note that the impact of dynamic XT variation[17, 18] has not yet been fully quantified. Dynamic variations in propagation delays between cores, relevant for SSC transmission and resource sharing[9] were also measured. For several core pairs of the 22-core fiber stayed below 3 ps over a 24 hour period under lab conditions, well below the symbol period of the utilized modulation.

Shared pilot-tone for spatial super channels

In SDM-SHD systems, one spatial channel may be used to transmit an unmodulated pilot-tone (PT) originating from the same transmission laser used to generate modulated signals on the remaining spatial channels[14]. The PT is used at the receiver to cancel the phase noise affecting the signals[10] and simplifying the required digital signal processing[19] at the cost of a small OSNR penalty and reduction of SE[20]. Previously, SDM-SHD has been used for high-capacity transmission with wide linewidth lasers[10] and networking demonstrations[13]. In the case of a 22-core HSM-MCF system, the PT core represents a 4.5% reduction in SE compared to equivalent intradyne detection (ID) system. Fig. 4 shows a comparison of the required OSNR for SHD compared to ID for transmission through the 22-core fiber system with comb transmitter using PDM-64-QAM. The OSNR penalty of SHD results from the degradation of the PT by noise, which may be minimized by filtering and/or increasing the PT OSNR. Using a 0.8 nm PT filter and PT/signal OSNR ratio of 1.5 dB yields a 0.9 dB penalty for SHD, matching the theoretical prediction[20].

Coding across spatial-super channels

Many spatial channels also opens up the possibility of applying multi-dimensional modulation formats[10-13] and/or coding across SSCs[13]. Recently, multi-dimensional modulation formats have been applied to SDM systems, clouding the distinction between optical modulation formats and optical domain forward-error-correction (FEC). Since SDM systems with over 100 spatial channels[6] have been reported, applying error-correcting codes over SSCs containing thousands of bits becomes feasible and adopting optical coding as an inner FEC code[19] becomes an interesting avenue of study.

Previously, linear block coding using shortened Bose–Chaudhury–Hocquenghem (BCH) codes was used to code SSCs modulated

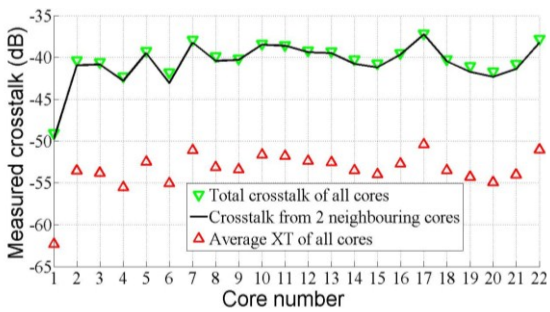

Fig. 3: Measured core-wise IC-XT for 22-core fiber

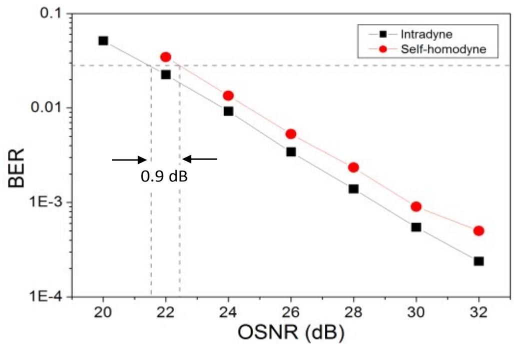

Fig. 4: OSNR penalty for SHD in 22-core fiber

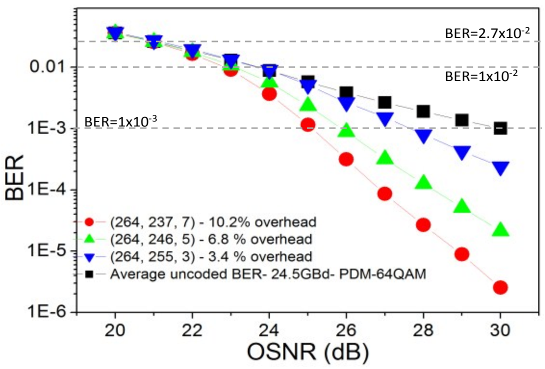

Fig. 5: BER vs OSNR after single span transmission of 22-core SSC with 3 coding schemes

with 25 GBd PDM-64QAM symbols in each core of a 19-core fiber. Over a single span, up to 3 dB reduction in OSNR requirement at a BER of $3.8x10^{-3}$ and a 54% increase in transmission reach for the same BER were achieved, corresponding to an increase of 122% at BER=$1x10^{-3}$.

Fig. 5 shows that similar improvement can be expected by applying extended BCH codes to the 22-core fiber system. 3 codes with overhead of 3.4%, 6.8% and 10.2% were investigated for 22-core SSCs fiber system. The 3 codes are capable of correcting 1, 2 and 3 errors per 264 bit block respectively, reducing the required OSNR for a BER=$1x10^{-3}$ by 2.3 dB, 4 dB and 5 dB respectively. As with the 19-core codes, the improvement reduces at higher BER thresholds as the number of errors per block increases.

Fig. 2 also shows how such a transmitter and fiber could be integrated with technologies such as joint-core reception and SSC coding. The uncoded BER shows a strong wavelength dependence with sub-channel BERs varying by over 3 orders of magnitude. Such variation may be problematic for the selection of outer FEC codes that are usually defined by fixed overhead and required input BER[21]. The variation of pre-FEC BERs is first reduced by averaging BER across channel groups. Indeed Fig. 2 shows that averaging over SSCs reduces the BER variation to just over one order of magnitude. Further system improvements may be gained by using some coding overhead to apply specific coded modulation depending on the quality of each SSC[13] to reach the target pre-FEC BER with the smallest possible overhead. Although SSCs may not be the optimum grouping strategy for such a system they allow short optical codes of 100s of bits to condition the pre-FEC BERs of serially coded outer FEC using 1000s of bits for optimizing the overall throughput.

Conclusions

Homogeneous, single-mode (HSM) multi-core fibers (MCFs) have thus far been used to demonstrate the largest per-fiber transmission capacity, the largest capacity-distance product and aside from multi-element fiber the lowest recorded inter-channel crosstalk of all forms of SDM. Although it is likely that few-mode MCFs will eventually offer greater per fiber capacity, HSM-MCFs require less drastic changes to transmitter and receiver hardware, offering a simpler migration path from currently installed systems. Whilst the impact of inter-core crosstalk in long-haul transmission has yet to be fully understood, the low dynamic skew between cores is expected to aid implementation of system features, such as shared receiver processing, pilot-aided transmission and multi-dimensional modulation.

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