# Wideband Transmission in Low Core-Count Multi-Core Fibers

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***Abstract*—We explore S, C + L-band transmission in low-core count multi-core fibers (MCFs). After reviewing progress in wideband transmission demonstrations in both SMF and MCFs we focus on two experiments demonstrating 57 km, 1 Pb/s transmission with 20 THz transmission bandwidth and 319 Tb/s transmitted over 3000 km in a 4-core MCF with standard cladding diameter. Finally, we briefly explore the potential benefit of increased spectral efficiency in MCF transmission by exploiting reduced (IC-XT) at lower wavelengths.**

***Keywords*—Space-division multiplexing, multi-core fibers wideband transmission, multi-band transmission**

## I. INTRODUCTION

Demand for enhanced optical transmission capacity [1] has fuelled research into new spectral windows [2] and new fibers supporting multiple spatial paths [3]. New transmission bands have been recently explored as a near-term solution to increase optical transmission capacity both for new fibers and to extend the lifetime of already deployed fibers. Space-division multiplexing (SDM) has been explored as a method of increasing transmission capacity at the same time as improving efficiency with the potential for both displayed in numerous experimental demonstrations [3]. Of the SDM fibers proposed thus far, weakly-coupled (WC) or uncoupled multi-core fibers (MCFs) are compatible with conventional transceiver technology and can be used without MIMO processing for spatial demultiplexing, making them the most likely candidates for first SDM fiber installations. However, the reduced mechanical reliability, production yield and splicing accuracy in larger diameter MCFs has led to practical interest in reducing the thickness of SDM fibers [3-6]. Fibers with the same 125 µm diameter as standard single-mode fibers (SMFs) are of interest being compatible with current cabling technology and have been widely explored in recent years, with the number of cores typically limited to 4 by the crosstalk (XT) levels required for C- and L-band wavelengths [4-6]. However, the wavelength dependence of inter-core (IC-XT) [6] means that shifting the transmission spectrum towards the S-band may not only increase data-rates in such fibers but also to potentially allow MCF designs with higher spatial density.

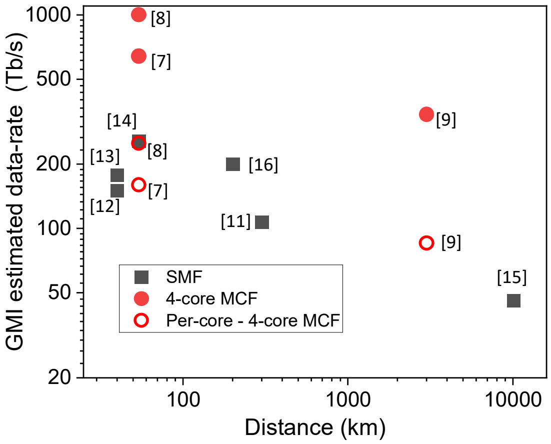

Fig. 1. Data-rate (GMI) vs transmission distance for >100 nm transmission in standard cladding diameter fibers

Here, we explore this intersection between research activities on SDM fibers and those on wideband transmission. After summarizing the state of the art of wideband transmission in both SMF and MCFs, we focus on two experiments including more than 1 Pb/s transmission of a near continuous bandwidth signal of more than 20 THz over a single span [8] and 342 Tb/s transmitted over 3000 km in a 4-core MCF [9, 10] with standard cladding diameter. Finally, we briefly explore the potential benefit of increased spectral efficiency in MCF transmission by exploiting reduced (IC-XT) at lower wavelengths.

## II. HIGH DATA-RATE SINGLE-SPAN S-, C- AND L-BAND TRANSMISSION DEMONSTRATIONS

A number of different amplifier combinations have been used to cover the extended spectral width spanning the S-, C- and L-bands. Semiconductor optical amplifiers have demonstrated >100nm amplification [11] and C + L-band erbium (E-) doped fiber amplifiers (DFAs), have been combined with several complimentary amplification schemes including distributed Raman amplification [12], thulium (T-) DFAs) [7] and discrete Raman amplification [13]. The same combination of TDFAs and distributed Raman amplification has subsequently been used to both extend the wavelength range of single span transmission [8, 14], enable long-haul [9, 10, 15], and transmission over 2 x 100 km spans [16]. In recirculating loop experiments, this amplifier combination enabled a data-rate. Estimated from the generalized mutual information (GMI) of 342 Tb/s transmission of 552 × 24.5 GBd, polarization-division multiplexed (PDM) 16-quadrature amplitude modulated (QAM) channels and up to in each core of a 4-core MCF [9, 10] and over 10,000 km SMF transmission cladding diameter fibers [15]. Fig. 1 shows a summary of transmission experiment utilizing more than 100 nm transmission bandwidth in standard. The points in red are discussed further in section III and include both per fiber and per core data-rates.

## III. 1PB/S & 3000 KM TRANSMISSION IN 125 µM MCF

Fig. 2 shows the experimental set-up for wideband transmission experiments comprising a non-measurement band of dummy channels and a sliding 3-channel test band. An optical frequency comb generated 25 GHz spaced carriers used for C/L-band dummy channels after modulation in a single-polarization (SP)-IQ modulator with a PDM emulation stage. After amplification in EDFAs, optical processors (OPs) or wavelength-selective switch, were used to both flatten the resulting spectrum and carve a sliding notch to accommodate the tunable test-band. The dummy channels of the S-band were

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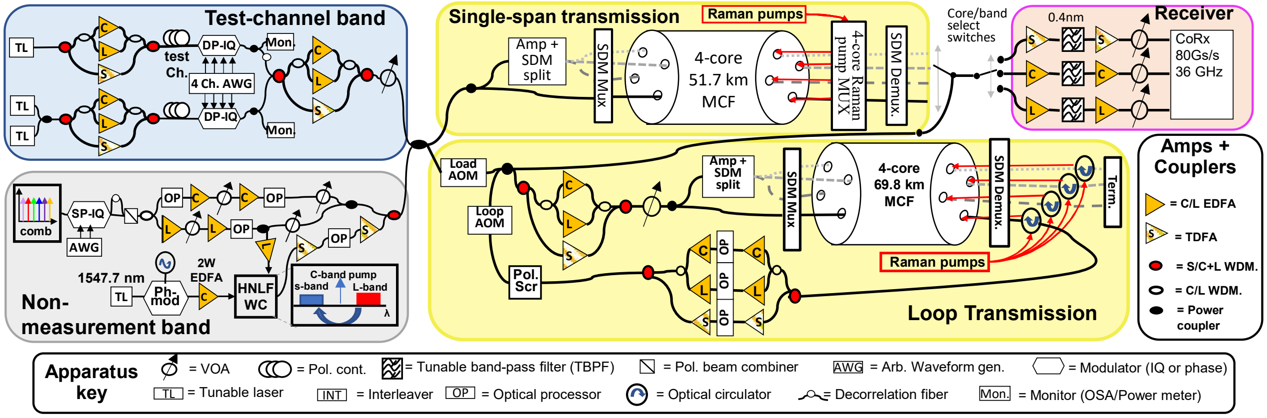

Fig. 2 Experimental set-up for single-span and recirculating wideband transmission experiments

produced by four-wave mixing based wavelength conversion a tap of the flattened L-band OP in a dispersion flattened highly-non-linear fiber (HNLF). The 1543.7 nm pump laser was phase modulated to suppress stimulated Brillouin scattering and amplified to over 2 W.

TDFAs with around 7dB noise figure were used to amplify S-band signals. The test-band consisted of a test-channel surrounded by two neighbor channels generated by narrow (<10 kHz) linewidth tunable lasers (TLs). Both were independently modulated in dual-polarization IQ-modulators (DP-IQ) driven by four arbitrary waveform generators (AWGs) operating at 49 GS/s. These produced 24.5 GBd, PDM-256QAM root-raised cosine shaped signals with a 0.01 roll-off of based on 216-1 bit pseudo-random binary sequences. For single span transmission, the combined test and dummy band signal was split and amplified for dummy spatial channels before transmission over a 51.7 km MCF. The input transmission spectrum was conditioned by the OPs to be roughly flat at the output of the fiber without any Raman amplification with per band launch powers of 18 dBm, 15 dBm and 14 dBm for S, C and L-bands, respectively, designed to counter stimulated Raman scattering (SRS). Backwards propagating Raman pumps were added in a multi-core pump module connected between the MCF and SDM de-mux with 4-core SC-connectors. Acousto-optic modulator (AOM) switches were used to gate optical signals for recirculating transmission. A 10dB power coupler split signals for recirculation and reception with the transmission path containing an amplification stage and 69.8 km span of 4-core MCF. Dummy spatial channels were generated from an amplified tap of the test-core before fiber transmission ensuring that for all distances all cores contained light that had traversed the same distance and launched at the same power. After the fiber was an additional amplification stage a per-band OP acting as a spectral gain equalizer, a polarization scrambler, and a second AOM switch.

For all measurements, the receiver path contained a 0.4 nm tunable band pass filter (TBPF) centered on the test-channel between 2 per band amplification stages. A VOA was used for power adjustment before a coherent receiver (CoRx) detected the signal using a <60 kHz nominal linewidth local oscillator (LO). The signals were digitized in a real-time oscilloscope operating at 80 Giga-samples/s and the traces stored for offline processing described in [10].

Figure 3 shows signal quality summaries for both reported experiments. Fig, 3 (a) shows the GMI estimated data-rate as function of wavelength across the 158.6 nm transmitted signal. The combined GMI estimated throughput of 1.02 Pb/s comprised 408.5 Tb/s from 335 S-band, 266.9 Tb/s from 200 C-band and 334.6 Tb/s from 266 L-band channels show the potential for ultra-wide WDM transmission with standard

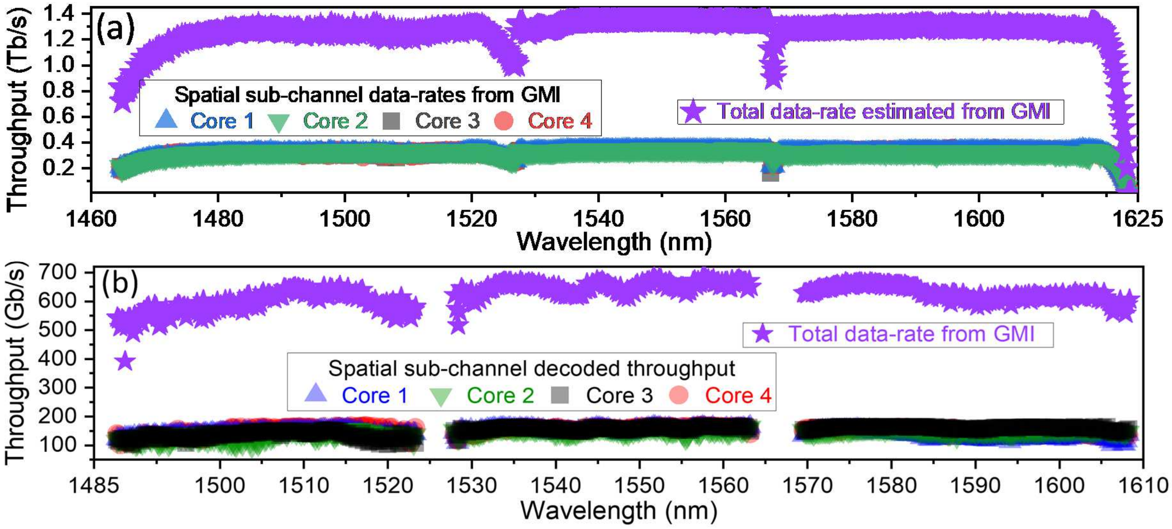

Fig. 3. GMI estimated Data-rate 802 PDM-256QAM 4-core spatial super channels from 1464.72 nm to 1623.35 nm after 54km transmission and (b) for 552 spatial super channels from 1487.8 nm to 1608.33 nm after 3001km

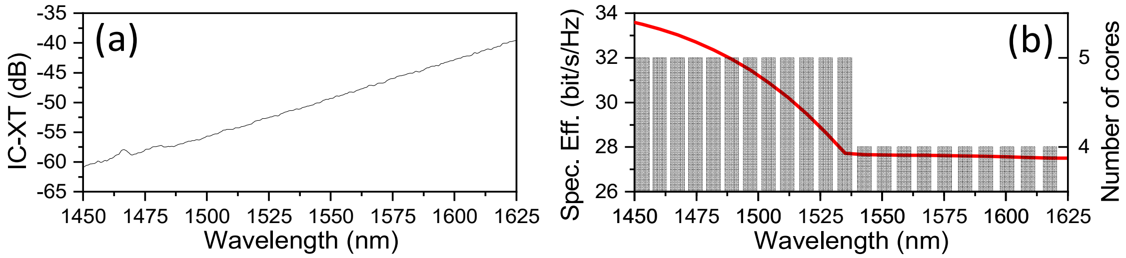

Fig. 4. (a) IC-XT and (b) Per-fiber SE in 25GHz spatial super channel in 50 km spaced, 2500 km link, vs wavelength in a 4-core 125 um wide MCF

coherent transceiver technology. Fig 3(b) shows the GMI estimated data-rates after 3001 km recirculating transmission for each of the 552 transmission channels. The total throughput of 342.8 Tb/s comprised 111.5 Tb/s from 189 S- band channels, 115.4 Tb/s from 178 C-band channels and 115.8 Tb/s from 185 L-band channels. The variation in signal quality across each band is conditioned by the combination of DFA and Raman gain profiles, and stimulated Raman scattering (SRS). For loop measurements, where signals pass many times through the same amplifier configuration, the signal quality closely follows the EDFA gain profiles, particularly in the C-band. The S-band data-rate profile resembling the TDFA gain profile with an additional tilt corresponding to the slope of the Raman gain profile, which, combined with higher fiber loss at low wavelengths, results in reduced achievable data-rate at lower wavelengths for both demonstrations. Particularly evident in Fig, 3(b) is the lower Raman gain for L-band channels where pump spectrum required for 1st order Raman gain is occupied by signal channels, highlighting a trade-off between S and L-band data transmission capacity. These results show that combining multi-band approach with low-core count MCF systems can bring per-fiber data-rates into the petabit/s regime whilst still being compatible with long-haul transmission and current transceiver and cabling technology.

## IV. SPATIAL SPECTRAL EFFICIENCY VS WAVELENGTH

Finally, we briefly investigate the impact of wavelength dependent inter-core crosstalk on the achievable spectral efficiency in homogeneous MCFs with the standard 125 µm cladding diameter. The limitation of core number in such fibers is largely conditioned by the core-pitch that leads to an acceptable level of IC-XT for the required system performance. However, lower confinement at higher wavelengths leads to a strong wavelength dependence of IC-XT, as illustrated from experimental measurements of crosstalk in a 4-core, 125 µm wide MCF for S, C and L-band wavelengths, in Fig. 4(a). Fig. 4(a) shows that IC-XT power varies around 20dB from low S-band wavelengths to the highest L-band wavelengths which raises questions about whether fibers optimized for S-band transmission with lower IC-XT levels could potentially allow a reduced core separation that permits additional cores within the same cladding diameter. This idea was explored in a simulation based on optimizing spectral efficiency in a 2500 km transmission link based on 50 km spans of 125 µm diameter, MCF, assuming a fiber with 5.6 µm core radius surrounded by 12 µm depressed cladding structure [7] and minimum of 30 µm between the center of each core and the cladding edge. For 25 GHz spatial super channels at wavelengths from 1450 nm to 1625 nm the core separation required for a IC-XT level to enable a specified signal-to-noise ratio was calculated along with the optimum number of cores this separation enabled according to an sphere packing algorithm. Based on the signal-to-noise ratio (SNR) and core number, disregarding non-linear impairments, the achievable spectral efficiency (SE) could then be calculated and compared. Fig. 4(b) shows the maximum achievable SE as well as the optimum core number for S, C and L-band wavelengths between 1450 and 1625 nm. It is shown that in this simplified case, moving from C to S-band wavelengths increases the optimum core number and achievable SE in the 125 µm diameter MCF.

## V. SUMMARY

We have summarized recent progress in ultra-wideband WDM transmission capability utilizing S-, C- and L-bands in both SMF and MCF and described 2 recent demonstrations in 4-core MCF with standard cladding diameter. Further, we have presented some simple analysis of the possibility of exploiting the reduced inter-core crosstalk at wavelengths below the C and L-bands to enable MCFs with smaller core pitch and potentially more cores in the same fiber diameter.

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