Long-Haul Transmission over Ultra-Low Attenuation and Crosstalk 4-Core Multicore Fiber

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Abstract: We report long-haul transmission up to 9000 km with conventional 75 km spans over 4-core multicore fiber with ultra-low attenuation (0.155-0.156 dB/km) and crosstalk supporting co-propagating and bi-directional transmission configurations with equal performance. © 2024 The Author(s)

1. Introduction

The steadily increasing demand for greater submarine cable capacity in recent years has motivated significant research into new fiber and system technologies that can enable future growth. One technology that has drawn significant industry interest in this regard is multicore fiber (MCF) [1-3]. Two general types of MCF have been fabricated and studied, i.e., weakly-coupled (or uncoupled) MCF and randomly coupled (or coupled-core) MCF. Significant progress has been demonstrated in recent years in lowering the attenuation of weakly-coupled MCF to approach or equal that of ultra-low-loss single-core fibers [4-7]. Three of those papers cited are for 2-core MCF, currently a primary industry focus [8]. 4-core MCF as studied here is a longer-term potential option to further increase cable capacities. The 4-core MCF in [5] had record-low attenuation ~0.155-0.157 dB/km in a 60 km span. Moreover, none of these fibers have been demonstrated in long-haul transmission experiments yet. On the other hand, a 4-core MCF was transmission-tested in a submarine cabled condition over long-haul distances up to 5350 km [9]. However, the attenuation of that fiber was 0.177 dB/km and the span length in the tests was 60 km, and only 100 Gb/s PM-QPSK signals were transmitted. More recently, a 4-core MCF with larger core effective area and 0.166 dB/km demonstrated bi-directional transmission up to 10,000 km using 65 km spans [10].

In this work, we investigate long-haul transmission over trans-oceanic distances with a 4-core weakly coupled MCF having core attenuations of 0.155-0.156 dB/km at 1550 nm over a 75 km span. The co-propagating crosstalk is also ultra-low at about -70 dB/km at 1550 nm. The attenuation of this fiber slightly improves upon that of [5] in a longer span length. We demonstrate 64 Gbaud transmission with optimized probabilistic constellation shaping (PCS) QAM signals out to 6000 km with an average spectral efficiency greater than 4 b/s/Hz. QPSK signals (more than 200 Gb/s per channel) are successfully received after 9000 km.

2. MCF characteristics and experimental configuration

Table 1: MCF characteristics

Characteristic	Value
Core pitch (μm)	44.4
Attenuation of cores 1-4 at 1550 nm (dB/km)	0.155, 0.155, 0.156, 0.156
1550 nm crosstalk (dB/km)	-70
1550 nm MFD (μm)	10.0
1550 nm dispersion (ps/nm/km)	18.5

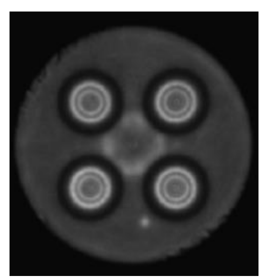

Fig. 1: 4-core MCF cross-section

The basic characteristics of the MCF are given in Table 1 and a cross-sectional view is shown in Fig. 1. Similar to [4,5], the cable cutoff of this fiber was somewhat higher than 1530 nm. The cores also include an offset index trench to reduce crosstalk and tunneling loss. The experimental re-circulating loop configuration is shown in Fig. 2. The measurement channel was encoded on an external cavity laser (ECL) with a dual-polarization I-Q modulator at 64 Gbaud with different modulation formats, driven by an arbitrary waveform generator (AWG) with bandwidth about 42 GHz. The two adjacent channels were modulated with a single-polarization I-Q modulator with inverted and delayed versions of two of the AWG drive signals. These two adjacent channels then passed through a polarization multiplexing emulator with ~200 ns relative delay. The remaining 54 channels were comprised of amplified spontaneous emission (ASE). All channels were combined with a WaveShaper (WS) tunable filter with 75 GHz channel spacing and launched into a re-circulating loop. The transmission fiber in the loop was comprised of a 75 km span of the 4-core MCF. The signals were launched into core 1 of the MCF and then sequentially into cores 2, 3, and 4 with amplification after each 75 km making the total loop transmission length 300 km, in a configuration like that in [9]. Before exiting the loop after K passes, the signals passed through all 4 cores K times. Details of the span construction are given in Fig. 3.

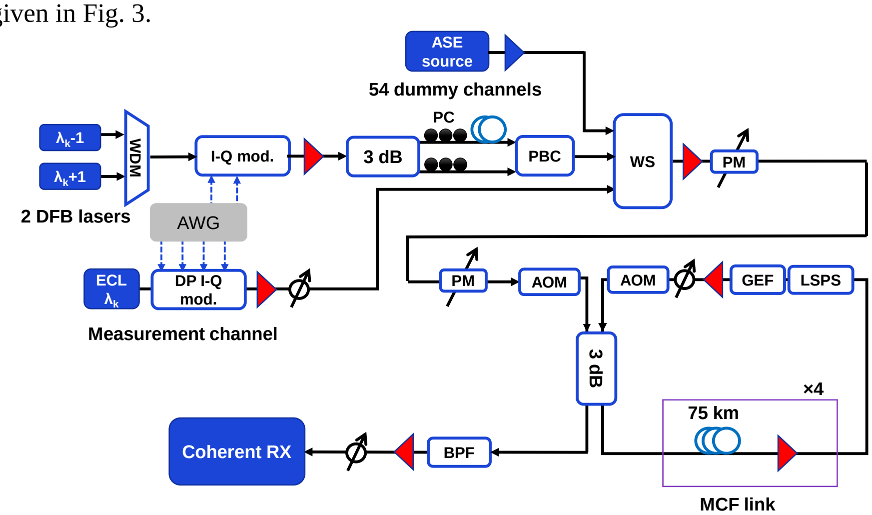

Fig. 2: Schematic illustration of experimental transmission set-up. PBC: polarization beam combiner, PM: power monitor, AOM: acousto-optic modulator, GEF: gain equalization filter, LSPS: loop synchronous polarization scrambler, BPF: bandpass filter.

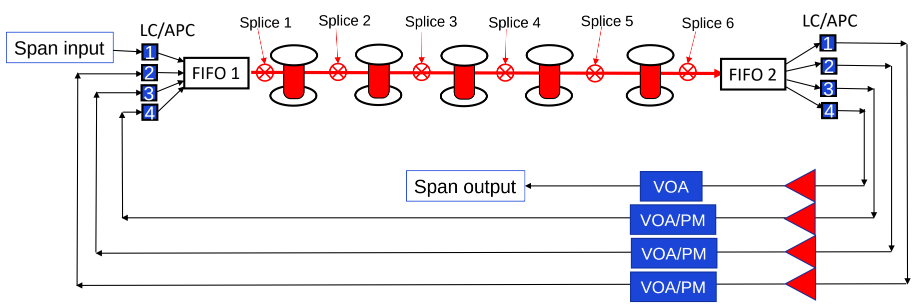

Fig. 3: Details of MCF link construction in co-propagating transmission configuration. VOA: variable optical attenuator, PM: power monitor.

As illustrated in Fig. 3, the MCF span was built from 5 individual reels having total length 75 km with a fan-in/fan-out (FIFO) device spliced at each end. There were 6 MCF splices overall. The average loss of each FIFO device was 0.27 dB. The average MCF attenuation was 0.156 dB/km across all cores and all 5 reels. The average MCF-MCF splice loss was less than 0.15 dB. Including connectors, the total average span loss through the 75 km MCF span was about 13.2 dB. Crosstalk (co-propagating) was measured through the full span with FIFOs attached and the total crosstalk experienced by each core was found to be -70 dB/km or less at 1550 nm.

3. Experimental Transmission Results

Due to the configuration of the re-circulating loop set-up, the maximum total launch power into each span was 15 dBm, or about -2.6 dBm per channel. This was about 2 dBm below the optimal nonlinear channel power but is consistent with power-constrained submarine SDM systems [11,12]. We began measurements by transmitting and detecting dual-polarization uniform 16QAM signals at 64 Gbaud first for co-propagating transmission (all cores propagating in the same direction in the MCF) and then for bi-directional transmission (adjacent cores propagating in opposite directions). Offline pilot assisted digital signal processing (DSP) with an overhead of 3.9% was employed for these signals. Results expressed in terms of spectral efficiency (SE) defined as

$$SE = 2\frac{B_{sig}}{B_{ch}}GMI(1-\varepsilon) \tag{1}$$

are given in Fig. 4a, where B_{sig} is the baud rate (Gbaud), B_{ch} is the channel spacing (GHz), GMI is the average generalized mutual information of each polarization, and ε is the overhead rate. The results are an average of 12 channels across the C-band as a function of distance out to 6000 km. There was no measurable performance difference between the co-propagating and bi-directional transmission configurations. This is consistent with the co-propagating crosstalk of about -70 dB/km as measured through the full span and predicted bi-directional crosstalk of about -90 dB/km, both of which should produce negligible SNR penalty significantly less than 0.1 dB [13,14].

To maximize fiber capacity and spectral efficiency, we then changed the modulation format to PCS-64QAM and PCS-16QAM signals and repeated the 12-channel measurements out to 6000 km for the co-propagating MCF configuration. The PCS shaping factors chosen at each distance were based on the measured SNR of the uniform 16QAM signals. These transmission results along with uniform QAM (64QAM and 16QAM) results are given in Fig. 4b. At each point, the maximum of the 64QAM and 16QAM spectral efficiency values was chosen for both the uniform and PCS signals. The average increase in spectral efficiency with the PCS-QAM signals was about 0.4 b/s/Hz from 300-6000 km. The general link distance regions for which each PCS-QAM format provided higher capacity are illustrated in Fig. 4b. Finally, we measured all 57 channels for two systems: the PCS-16QAM signals at 6000 km, and QPSK signals at 9000 km. The results are given in Fig. 5, expressed as channel capacity defined by the measured GMI value, i.e. channel capacity = $2 * B_{sig} * GMI * (1-\varepsilon)$. For the QPSK signal transmission, blind DSP was used with no overhead ($\varepsilon = 0$). The average channel capacities were 327 Gb/s at 6000 km and 226 Gb/s at 9000 km.

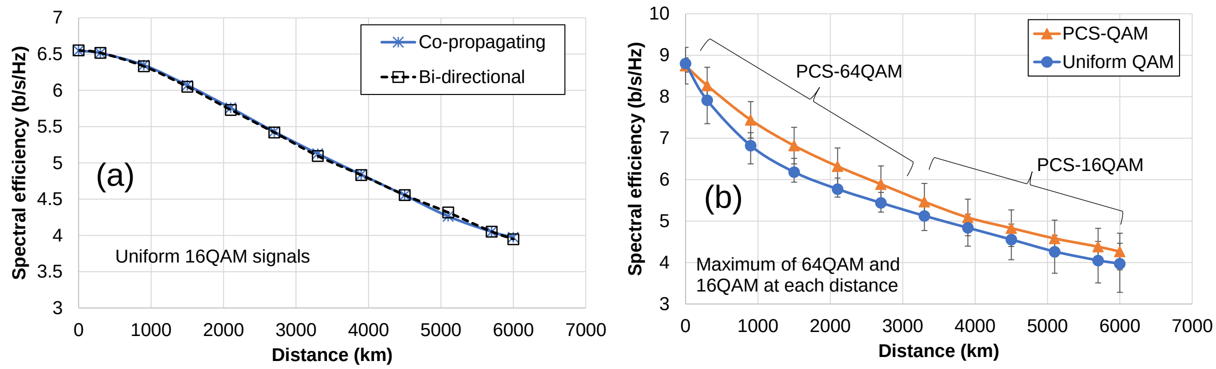

Fig. 4: a) SE as function of distance for co-propagating and bi-directional MCF transmission of uniform 16QAM, b) SE as function of distance for uniform QAM and PCS-QAM signals in co-propagating configuration.

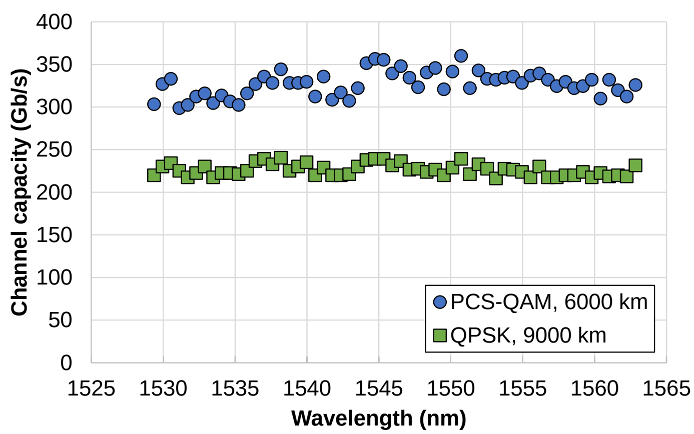

Fig. 5: Channel capacity for all channels: PCS-QAM at 6000 km and QPSK at 9000 km.

4. Summary

We demonstrated trans-oceanic length transmission over an ultra-low attenuation (0.156 dB/km) and crosstalk 4-core MCF in 75 km spans. The low crosstalk enabled co-propagating and bi-directional transmission with equivalent performance. Using optimized PCS-QAM modulation, we achieved an average channel data rate of 327 Gb/s, or SE ~4.3 b/s/Hz at 6000 km. QPSK signals were measured after 9000 km transmission with average SE 3.0 b/s/Hz.

5. References

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