Long-Haul Unidirectional Transmission over Weakly-Coupled MCF with Distance-Insensitive Inter-Core Skew Spread

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Abstract: We demonstrate unidirectional 3000-km transmission over homogeneous step-index weakly-coupled multi-core fiber. Distance-insensitive pulse broadening is obtained by inline core-permutation without any fan-in/fan-out device, enabling inter-core-crosstalk cancellation at 3000 km only with 3-ns-processing window in MIMO-DSP. © 2023 The Author(s)

1. Introduction

Increasing transmission capacity per optical fiber is attained by an approach of space division multiplexing (SDM) technology, aggregating multiple spatial channels in spatially-structured fibers. Although multi-core fiber (MCF) with weak inter-core coupling will relatively offer seamless upgrade for next generation's optical transport systems due to its advantage of optical compatibility to existing single-mode fiber (SMF) systems [1], extending achievable transmission reach with dense core packing while keeping standard cladding diameter of 125 μm is technically challenging due to coupling effects among spatial channels even with the use of weakly-coupled (WC) MCFs. One may deal with spatial channel coupling effects, or referred to as inter-core crosstalk (IXT) when the phenomenon is undesired, by digital decoupling through multiple-input multiple-output digital signal processing (MIMO-DSP) technique, generally requiring high computational loads. One reason for this is required memory length, characterized by inter-core skew (ICS)-induced impulse response broadening, reaching more than several tens/hundreds of nanoseconds in homogeneous/heterogeneous WC-MCFs [2]. As a suppression approach of pulse broadening in WC-MCF links, inter-core skew (ICS) compensation was demonstrated in [3], while still requiring prior knowledge of ICS in each core and insertion of fan-in/fan-out (FI/FO) devices at ICS compensation points. Alternative strategy to avoid IXT impact in standard cladding WC-MCF transmission includes bidirectional propagation-direction assignment [4] or low-IXT fiber design with trench-assisted refractive index profile [5].

In this work, we demonstrate a long-haul unidirectional step-index (SI) MCF transmission over a distance of 3000 km with a novel transmission technique for ICS suppression in WC-MCFs. By developing cyclic mode permutation (CMP) originally designed for mode-multiplexed transmission links [6], a technique in the presented work, referred to as cyclic core permutation (CCP), is directly introduced inline via periodic fusion splicing with different core contacts. We show that CCP scheme over WC-MCF yields distance-insensitive pulse broadening in weak coupling region, hence greatly relaxing a requirement on MIMO-DSP for IXT cancellation. Figure 1 compares memory length requirement on MIMO-DSP reported in recent SDM-MIMO transmissions over several types of SDM fibers. Even after 3000-km transmission over WC-MCF with inherent ICS of 1.1 ns/km, achieved memory length remained below 3 ns, which is comparable to low modal dispersion SDM fibers including coupled-core MCFs (CC-MCFs) [7-11].

2. Working Principle of Inline Cyclic Core Permutation in Weak Coupling Region

In weakly-coupled multi-span MCF systems, pulse broadening grows in a linear fashion along transmission line due to a presence of different ICS, originating from propagation constant difference in each core. Pulse broadening

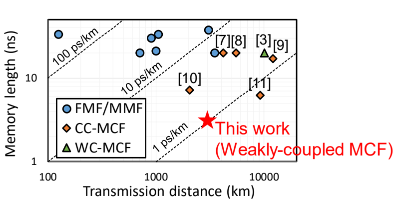

Fig. 1. Recent SDM-MIMO transmission experiments with memory length.

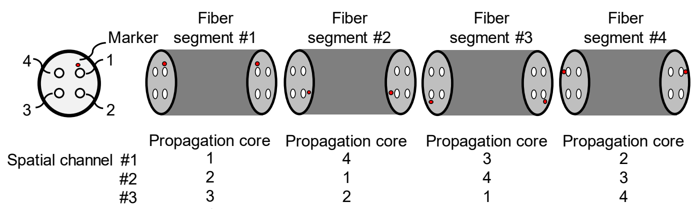

Fig. 2. Schematic of inline cyclic core permutation (CCP) in MCF application to square lattice four-core arrangement.

suppression scheme was proposed in [3] as ICS compensation by inserting optical SMF delay lines via FIFO devices. Alternative approach of CCP presented in this work is illustrated schematically in Figure 2. In CCP scheme, each MCF section is divided into N segments with equal length, and connected directly by, say, fusion splicing at a specific rotational angle that satisfies a condition of core contact with dissimilar ICS characteristics. After one cyclic period of CCP over a distance of L, each spatial channel propagates over all cores with a relative delay ΔT_i:

$$\Delta T_i = \sum_k \tau_k (L/N) = \sum_k (\tau_k/N) L, \quad (1)$$

where τ_i denotes relative ICS per unit length at an i-th core. Eq. (1) indicates that net ICS effect is "averaged" at every core, hence all spatial channels are expected to propagate in MCF links with equal group velocity. Compared to our previously-proposed similar approach of CMP designed for mode-multiplexed links [6], CCP technique is advantageous in that an introduction of inline CCP with fusion splicing instead of FIFO devices avoids additional insertion loss. It also requires no prior knowledge of ICS in each core. Technical challenges lie in requirement of multiple fusion splicing and specially designed fiber that has an "uniformity" along L. Accordingly, CCP technique may be suitable for terrestrial link applications, while the main scope of this work focuses on clarifying ICS equalizing performance under an assumption of above conditions are ideally satisfied.

To assess ICS equalizing effects, we perform a numerical simulation using a two-core MCF model with IXT and $\{\tau_1, \tau_2\}$ are -24.5 dB/span and {0.3 ns, -0.3 ns}/span, respectively. CCP cycle parameter in each span, denoted as σ_{CCP}, is varied with {0.125, 0.25, 0.5}, corresponding to cases where CCP is repeated at 8, 4, 2 times in each span, respectively. Figure 3(a) shows IXT accumulation along span. Fig. 3(b) represents sum magnitude of impulse response after 10, 50, and 150 spans with σ_{CCP} of 0.25. Regardless of span count, signal energy was well confined in the time window of $\pm$0.15 ns (hereinafter denoted as region-I), corresponding to time of flight of optical pulse and IXT during one cycle period of CCP. Rest energy located in slower/faster window out of $\pm$0.15 ns (denoted as region-II) attributes to second-order inter-core crosstalk (SO-IXT) and higher-order ones, arising from partial coupling back and forth between both cores [3]. The dissipation of pulse energy into region-II is understood by the property of SO-IXT that it partially drifts with group velocity different from that expressed in Eq. (1). Required memory length evolution, defined as a time window covering pulse energy of 99.9%, is evaluated in Fig. 3(c), showing a distance-insensitive property until it reaches some specific distance (~100 spans). Denoting h as a power coupling coefficient of IXT, a distance at which impulse response begins to spread is predicted by considering growth rates of IXT and SO-IXT, approximately given by hL and $(hL)^2$, respectively [12, 13]. At a shorter distance where SO-IXT is negligible as $hL \gg (hL)^2$, pulse energy mainly wanders in region-I and exhibits distance-insensitive temporal growth. With increased transmission reach, SO-IXT grows quadratically, and finally reaches to the regime of $hL \sim (hL)^2$ where impulse response broadens in accordance with the increased reach. In a consideration of CCP applications to homogeneous SI-MCF with IXT at the order of -30 dB/km at 1550 nm [1], above results give a prediction of distance-insensitive pulse broadening to be around 10^3 km, covering the major applications for long-haul terrestrial link systems. Another important consequence is that a width of pulse broadening in region-I is determined by σ_{CCP}: lower σ_{CCP} achieves narrower pulse broadening and vice versa. A cost will be an increase of undesired loss and IXT at splicing points, while this may be addressed by a high-accuracy low-loss MCF fusion splicing technology [14].

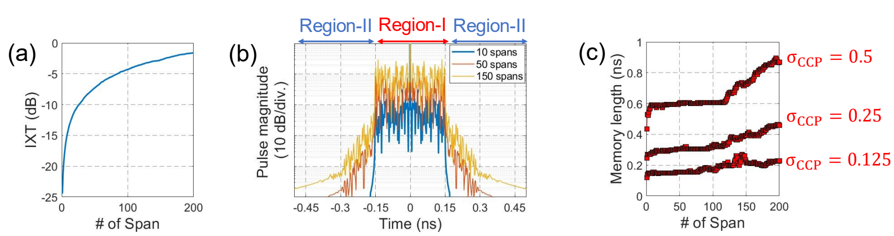

Fig. 3. Simulation results. (a): IXT accumulation along span increase. (b): Sum magnitude of impulse response at spans of {10, 50, 150}. (c): Memory length evolution along span increase when σ_{CCP}={0.125, 0.25, 0.5}.

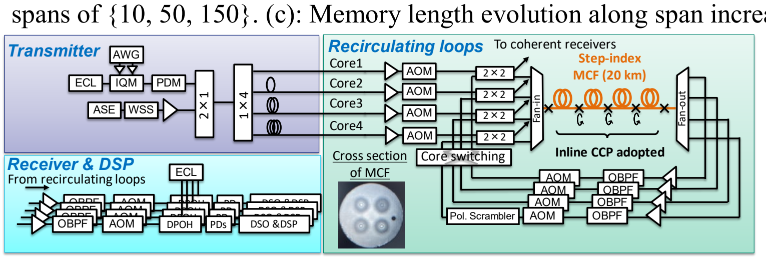

Fig. 4. Experimental setup.

Table 1. Parameters of SI-MCF

Parameter	Value
Attenuation	0.19 dB/km
Cladding diameter	125 μm
Core pitch	40 μm
Inter-core XT	-40 dB/km
Inter-core skew	<1.09 ns/km

Note: Evaluated at 1550 nm.

3. Experimental Setup and Results

The setup for a long-haul four-core SI-MCF transmission is depicted in Figure 4. Ten WDM channels and a test channel of 12-GBaud PDM-QPSK signal, located from 1549.556 nm to 1550.558 nm, were respectively generated from WSS-shaped ASE source and IQ-modulator, combined, and delayed to emulate four SDM channels at the C-band. Signal bit pattern of the test channel was coded by 25%-overhead (OH) LDPC code and also assumed BCH(30832, 30592) coding, yielding a normalized general mutual information (NGMI) threshold of 0.836 [15]. The channels then propagated over four-fold recirculating loop systems containing EDFAs, OBPFs, AOMs, four-core homogeneous SI-MCF, and FI/FO devices. 20-km-long MCF was comprising four spools with an equal length of 5 km, connected through MCF fusion splicing based on CCP scheme with a rotation angle of $\pi/2$. Thereby CCP cycle in each span σ_{CCP} was 1. We found that ICS was greatly reduced less than 1 % (from 1.09 ns/km to 0.01 ns/km) after CCP-adopted SI-MCFs. Residual ICS might arise from differences in SMF inputs of FI/FO devices. Each end of recirculating loop systems was mutually switched to make each spatial channel experience different core path at the subsequent span. Note that, with CCP scheme, above switching is not always mandatory, while we introduced it to further enhance signal performance. Other fiber parameters were listed in Table 1. At the receiver, four spatial channels were detected through a coherent SDM reception setup, and processed by off-line MIMO-DSP containing chromatic dispersion compensation, 8×8 MIMO frequency-domain equalization (FDE), and carrier phase recovery.

Figure 5(a) represents a wavelength-dependent IXT of SI-MCF including FIFO devices in the C-band. IXT varies in the range of -42 to -38 dB/km, indicating that, based on the discussion in Section 2, distance-insensitive pulse broadening with weak coupling will be observed in the range up to ~10^4 km with the use of the SI-MCF. Impulse response evolutions at 1550.057 nm over core#1 are drawn in Fig. 5(b), showing a distance-insensitive temporal growth with pulse energy confinement within 3-ns time window at every distance. Distinct peaks in the figure could be induced by misalignment at MCF splicing. We confirmed that equalizer coefficient length of 72 was sufficient to cover 3-ns window for MIMO-DSP-based IXT cancellation in transmission at 3000 km. Memory length evaluated at short and long wavelength channels is shown in Fig. 5(c). At both wavelength channels, "flat" evolution was obtained by CCP scheme, indicating a feasibility to apply the scheme to the entire C-band. We then performed long-haul 11-WDM transmission over SI-MCF with IXT cancellation. Signal performance at 3000 km is summarized in Fig. 5(d) at all wavelength/spatial channels, confirming that long-haul unidirectional homogeneous SI-MCF transmission over 3000 km was successfully demonstrated.

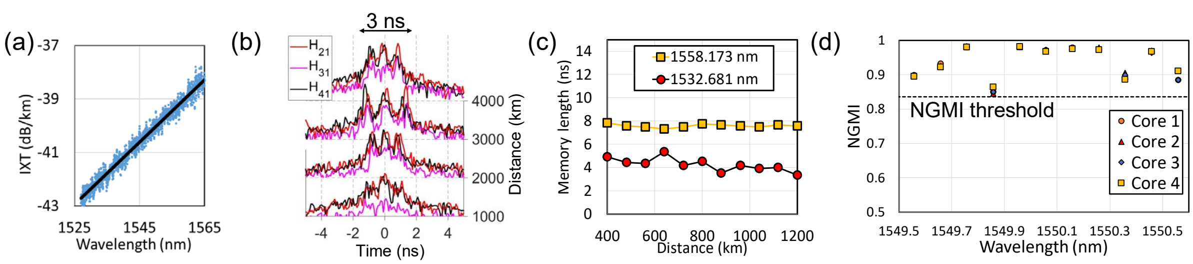

Fig. 5. (a): Wavelength-dependent IXT in C-band. (b): Impulse response evolution at core#1. (c) Memory length required for MIMO-DSP at edge channels in C-band. (d): NGMI for all wavelength/spatial channels at 3000 km.

4. Conclusion

We have presented a long-haul unidirectional transmission over homogeneous step-index MCF with a distance of 3000 km. We showed that cyclic core permutation (CCP) enabled group velocity in each core to be equalized, hence acquiring distance-independent pulse spread in weak coupling region. Based on the advantage of CCP to be directly introduced inline with fusion splicing, ICS reduction to less than 1 % in 20-km-long MCF transmission line was achieved. Digital IXT cancellation was performed by MIMO equalization only with 3-ns window at 3000 km, which is comparable to that observed in transmissions over low modal-dispersion coupled core MCFs.

5. Acknowledgement

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