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Performance Enhancement of Multi-Core Fiber Transmission Using Real-Time FPGA Based Pre-Emphasis

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Abstract: We experimentally demonstrate pre-emphasis based performance for a 2 km long 7-core multicore fiber link. Simultaneous transmission below the FEC threshold is achievable for all cores by using signal equalization in a FPGA.

OCIS codes: (060.2270) Fiber characterization; (060.2360) Fiber optics links and subsystems.

1. Introduction

As single-core single-mode fiber (SC-SMF) approaches its fundamental limit of 100 Tbps due to limitations from amplifier bandwidth, nonlinear noise and fiber fuse phenomena [1], multicore fibers (MCFs) offer scaling of transmission capacity through space division multiplexing (SDM). Apart from data communications, MCF technology is also being considered for microwave photonics applications such as multi-cavity optoelectronic oscillators [2], and signal processing [3], since it offers identical mechanical and environmental conditions for all parallel cores. Several experimental results have been reported regarding the implementation of SDM in systems with MCFs, including 109 Tbps in a 7-core fiber [4], 112 Tbps in a 7-core fiber [5], 305 Tbps in a 19-core fiber [6], and 1.02 Pbps in a 12-core fiber [7]. Furthermore, MCFs have also been implemented in fiber-wireless links such as a full duplex, 802.11ac-complient, 3×3 Multiple-Input Multiple-Output (MIMO) system using 7-core fiber [8], and Centralized Radio Access Networks (C-RANs) [9].

However, crosstalk between neighboring cores is a fundamental limitation of MCFs in SDM applications. Crosstalk fundamentally arises due to power coupling between the adjacent cores during signal propagation and can be determined from the structural parameters of MCFs. Imperfect splices and multicore erbium doped fiber amplifiers also affect crosstalk [10]. There are basically two known approaches for crosstalk reduction: (i) the first is to reduce the coupling coefficient between the cores in a homogeneous MCF, as in trench-assisted or hole-assisted MCFs [1]; (ii) the second approach is to introduce an intrinsic index difference between the adjacent cores, resulting in heterogeneous core MCFs. In addition to modified MCFs, offline digital signal processing (DSP) techniques and MIMO equalization [5,11], have been used to reduce the impact of crosstalk in strongly coupled 3-core MCFs. However, DSP introduces additional latency in the system which is undesirable in applications such as 5G networks [12].

In this paper we characterize a 2 km long 7-core MCF and experimentally demonstrate a low-latency, FPGA-based real-time transmissions. By means of adaptive pre-emphasis, deterministic distortions due to the limited bandwidth of the link are compensated. Experimental results show that a 2.5 Gbps non-return-to-zero on-off-keying (NRZ-OOK) modulated signal in each core can be transmitted with a BER level below the FEC limit, enabling post-FEC error-free transmission.

2. Characterization of the Multi-Core Fiber

We characterized the crosstalk level and insertion loss of a 2 km 7-core MCF. To measure the pairwise crosstalk and insertion loss of the MCF fiber, we launched optical power from a laser diode to each one of the cores in turn and measured the output of each core with a high sensitivity optical power meter, thus obtaining a 7×7 coupling matrix. Fig. 1(a) shows the measured pair-wise power coupling between all 7 cores. The total crosstalk, summation of each core contribution is shown in Fig. 1(b). The central core (core 0) exhibits the highest crosstalk as expected and other outer cores (1,2,4,6) have roughly equal crosstalk where core 3 and core 5 are much lower and higher than the other outer cores, respectively.

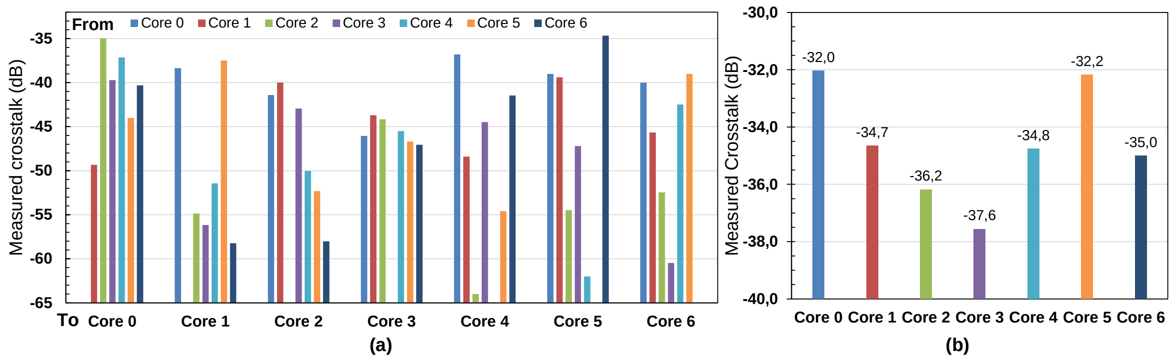

Fig. 1: (a) Measured pairwise crosstalk between cores and (b) measured total crosstalk per core.

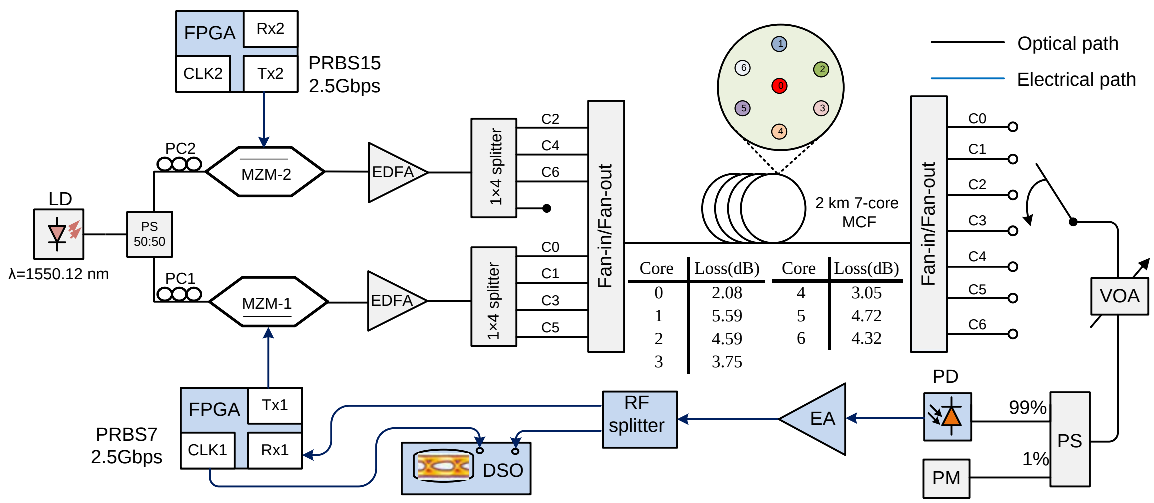

Fig. 2: Experimental setup for BER and eye diagrams measurements.

LD: laser diode, PS: power splitter, PC: polarization controller, MZM: Mach-Zehnder modulator, FPGA: field-programmable gate array, PRBS: pseudo-random binary sequence, EDFA: erbium-doped fiber amplifier, C: core, MCF: multicore optical fiber, VOA: variable optical attenuator, PM: optical power meter, PD: photodiode, EA: electrical amplifier, DSO: digital storage oscilloscope.

3. Experimental Setup

Fig. 2 shows the experimental setup for BER measurements and signal quality characterization, which includes a 2 km long 7- core MCF with 4 transmission channels (cores 0,1,3,5) and 3 interfering channels (cores 2,4,6). The output of the laser source is divided by a 50:50 power splitter to the input of two quadrature biased Mach-Zehnder modulators (MZMs): MZM-1 (bias point 1.2 V) and MZM-2 (bias point 4.6 V). Polarization controllers (PC1, PC2) are placed before the MZMs to reduce polarization dependent loss. An Altera Stratix V FPGA module that contains 7 transceiver channels is used to generate data streams and estimate the BER. MZM-1 and MZM-2 are modulated by 2.5 Gbps OOK signals generated from the FPGA module transmitters with PRBS7 and PRBS15 bit patterns, respectively. The modulated output from the MZMs is split by a 1×4 power splitter after being amplified by erbium-doped fiber amplifiers (EDFAs). The 1×4 splitter's outputs are connected to the inputs of the MCF's cores via a fan-in module. One of the MCF's outputs is connected to photodetector through a variable optical attenuator (VOA) for BER measurements. The signal into adjacent outer cores is decorrelated by transmitting PRBS7 in cores 0,1,3,5 and PRBS15 in 2,4 and 6.

The detected electrical signal is then amplified by a 26 dB broadband RF amplifier and divided into two paths; one is connected to a digital storage oscilloscope (DSO) to display the eye diagram and the second is connected to the receiver part of the FPGA for BER estimation. During the experiments, the optical power of each core was kept nearly equal.

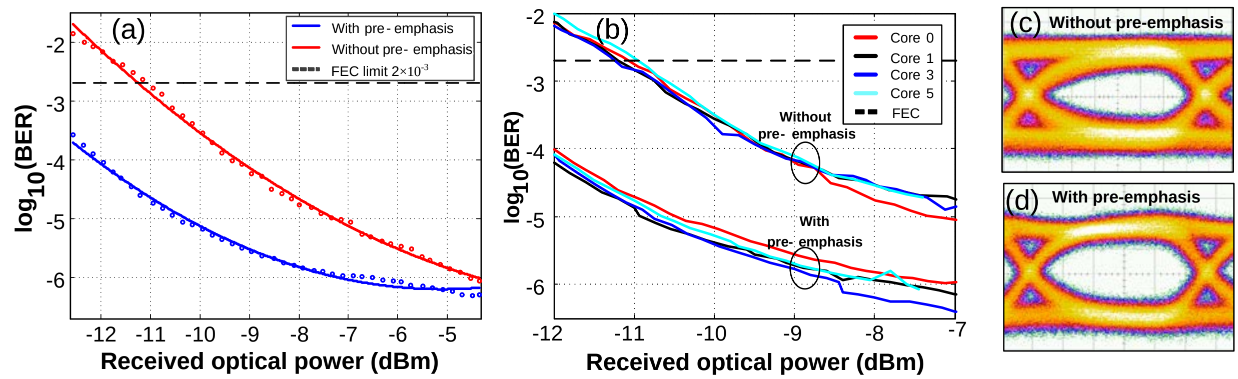

Fig.3: Comparison of measured BER versus received optical power of a 2.5 Gbps NRZ-OOK signal with and without FPGA equalization enabled (a) for central MCF core (core 0) (b) central core 0 and outer cores 1, 3 and 5. Eye pattern of the received 2.5 Gbps signal (c) without equalization and (d) with FPGA equalization for central MCF core 0.

4. Results and Discussion

The obtained BER of core-0 in response to received optical power at photodiode (PD) is shown in Fig. 3 in two different scenarios, with and without signal pre-emphasis for mitigation of signal distortions. Applying the FPGA pre-emphasis option we can reduce the effect of distortions in each core and the BER is far below the level of the forward error correction (FEC) limit as shown in Figs. 3(a) and 3(b). The measured optical output power of core 0 after 2 km MCF transmission varied from -12.55 to -4.35 dBm, where the 2.5 Gbps NRZ-OOK signal's BER without equalization was from 1.4×10^{-2} to 8.7×10^{-7}, but with equalization it varied from 2.6×10^{-4} to 5.1×10^{-7}, as shown in Fig. 3(a). Eye diagrams of the received signal without any signal equalization and with FPGA equalization are shown in Figs. 3(c) and 3(d).

5. Conclusions

Results show that by using FPGA pre-emphasis function the crosstalk is minimized and the BER value of received signals for each of seven MCF cores is reduced. Hence FPGA-based real-time multicore fiber technology is a viable solution for future high speed and high capacity communications.

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