Experimental Evaluation of the Crosstalk Impulse Response of a Temperature Controlled Homogeneous Multi-Core Fiber

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Abstract *We evaluate the temperature dependence of the impulse response of a multi-core fiber. We show a delay dependence of 40ps/km/°C and negligible variation of the duration of the impulse response with temperature.*

Introduction

Weakly-coupled homogeneous multi-core fibers (MCFs) have been extensively proposed as a spatial-division multiplexing (SDM) transmission media due to the relatively simple transition from conventional single-core fiber systems[1]. MCFs provide a substantial increase of the spatial spectral efficiency whilst allowing all-optical spatial multiplexing and demultiplexing, thanks to a relatively weak interaction between cores[2]. This has lead to the proposal of MCFs for applications ranging from short optical inter-connects in intra-datacenter networks[3] up to high-capacity wideband trans-continental transport links[4]. In addition, MCFs support sharing of hardware resources and digital signal processing (DSP)[5], simplified switching through the use of spatial-super-channels[6], and multi-dimensional modulation across spatial channels[7]. However, these applications rely on weak inter-core crosstalk (IC-XT) as well as low differences in propagation delay between cores, referred to here as inter-core skew (ICS). As MCF-based systems are under consideration for field deployment[8], it becomes increasingly relevant to address the impact of environmental conditions on IC-XT and ICS[9]–[11]. It has been shown that these transmission characteristics can be jointly addressed by evaluating the impulse response[12]. Nevertheless, the impact of the environmental conditions on the impulse response of MCFs is yet to be studied, which is fundamental for the future development of IC-XT and ICS mitigation mechanisms.

Here, we address the impact of changes in temperature on the crosstalk impulse response of a MCF. This is performed using a digital-signal processing (DSP) based technique similar to a previously developed method for few-mode fibers[13]. For this purpose, a reference signal is transmitted through a core of a MCF. The crosstalk produced by that signal into the other MCF cores is coherently detected and used to estimate the fiber impulse response. This approach is used to evaluate the impact of varying temperature on the crosstalk impulse responses of a 53.7 km 7-core MCF placed within a thermal chamber. It is shown that the total propagation delay varies as much as 40 ps/km/°C for all considered core pairs. The duration of the crosstalk impulse responses ranges from 2.3 ns to 20.2 ns, in agreement with previous work[14]. However, it is shown that the duration of the impulse response remains approximately unchanged with temperature. These results provide insight on the behavior of the impulse response of MCFs subject to varying environmental conditions and may be useful for the design of IC-XT and ICS compensation mechanisms.

Experimental Demonstration

Fig. 1 shows the experimental setup. At the transmitter, a frequency comb generator was used as light source with a band-pass filter (BPF) to select a single carrier at 1605 nm. This wavelength was selected since it leads to higher MCF crosstalk than a more conventional wavelength of 1550 nm. After amplification by an erbium-doped fiber amplifier (EDFA), the carrier was modulated by a dual-polarization dual-parallel Mach-Zehnder

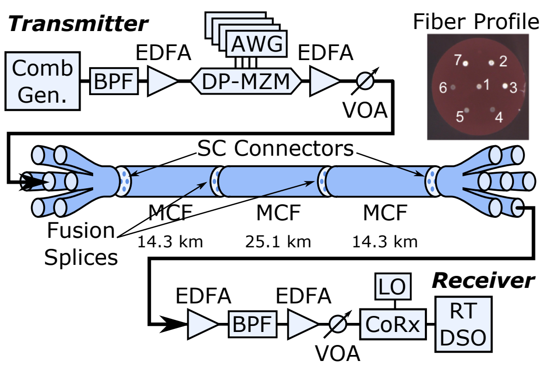

Fig. 1: Simplified diagram of the experimental setup.

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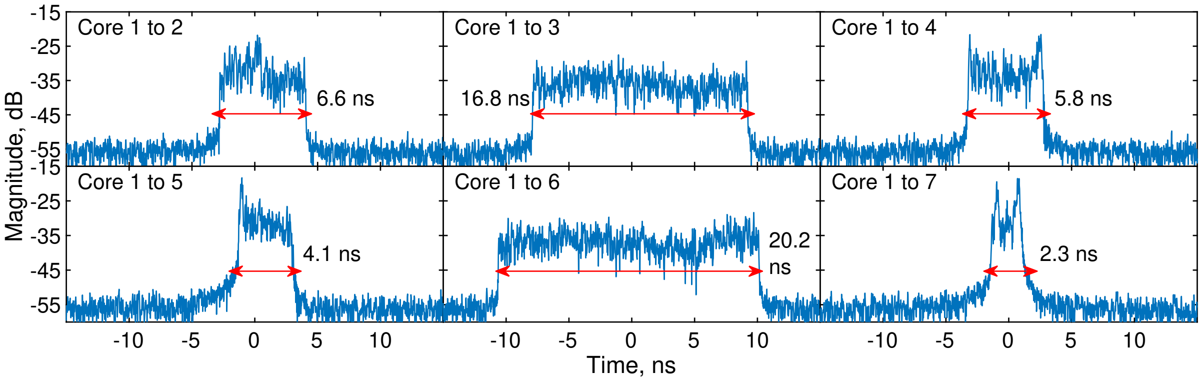

Fig. 2: Crosstalk impulse responses at room temperature from the central core (core 1) to the outer cores (cores 2 to 7). The estimated duration of the impulse responses are indicated for each case.

modulator (DP-MZM) driven by 4 arbitrary waveform generators (AWGs). The AWGs operated at 49 GS/s to generate a 24.5 GBaud polarization-multiplexed quadrature phase-shift keyed (PM-QPSK) signal with a root-raised cosine pulse shape and a roll-off of 0.01. An EDFA followed by a variable optical attenuator (VOA) was used to set a launch power of 8 dBm. The signal was launched into the center core of a 53.7 km 7-core homogeneous MCF. The fiber was composed of 3 spools, two of which were 14.3 km in length, and the other 25.1 km, as shown in Fig. 1. It had a cladding diameter of 160 µm containing step-index profile cores with a pitch of 44.3 µm. The spools had an average radius of 100 mm. The crosstalk between the center core and each of the outer cores averaged at -42 dB at a wavelength of 1550 nm, increasing to -35 dB at the operation wavelength of 1605 nm. The fiber input and output were connected to fused-fiber fan in/outs through 7-core SC-type connectors. After transmission, the crosstalk signal from one of the outer cores was sent to a receiver. The power of the crosstalk signal at the receiver input was around -40 dBm. To recover it, we used two EDFAs with a 5 nm BPF in-between to pre-amplify the signal before detection, with a VOA for power control. The signal was detected at a polarization-diverse coherent receiver (CoRx), where it was mixed with a $<$60 kHz linewidth free-running local oscillator (LO). The detected signal was digitized by a real-time digital sampling oscilloscope (RT-DSO) operating at 80 GS/s, which was triggered by the pattern trigger of the AWGs. For each measurement, we used a single 20 µs trace with 4.9×10^5 symbols. Signal recovery was performed offline using MATLAB and C. It consisted of resampling the incoming signal to 2 samples per symbol, followed by normalization, frequency-domain dispersion compensation and a rough data-aided carrier frequency estimation stage. The resulting signal was then used as the target signal for a 2$\times$2 multiple-input multiple-output (MIMO) with 3500-tap equalizers updated using a DA-LMS algorithm. As a consequence, the impulse responses of the MIMO equalizers approximate the impulse response of the crosstalk generation process between the pair of cores under analysis. Fine data-aided carrier phase estimation and recovery was performed within the MIMO update loop.

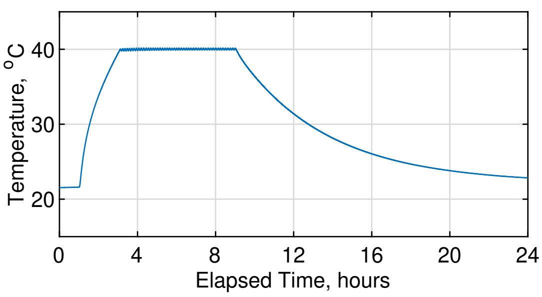

Fig. 3: Temporal evolution of the temperature within the thermal chamber.

Results

To simplify the visualization of the impulse responses, the following will use the magnitude of the impulse responses, defined here as the sum of the magnitudes of the impulse responses of the 2$\times$2 MIMO equalizers. Fig. 2 shows the magnitude of the impulse responses obtained when illuminating the center core 1 and measuring the crosstalk signals at the remaining cores. To estimate the memory length of the system, we arbitrarily defined the temporal duration of the impulse responses as the time interval containing 99% of the total energy. The corresponding values for each core pair are shown in Fig. 2. It is shown that the duration varies substantially between 2.3 ns and 20.2 ns. The relatively large range of values for the duration of the impulse responses may be partly explained by small differences in the propagation characteristics of the

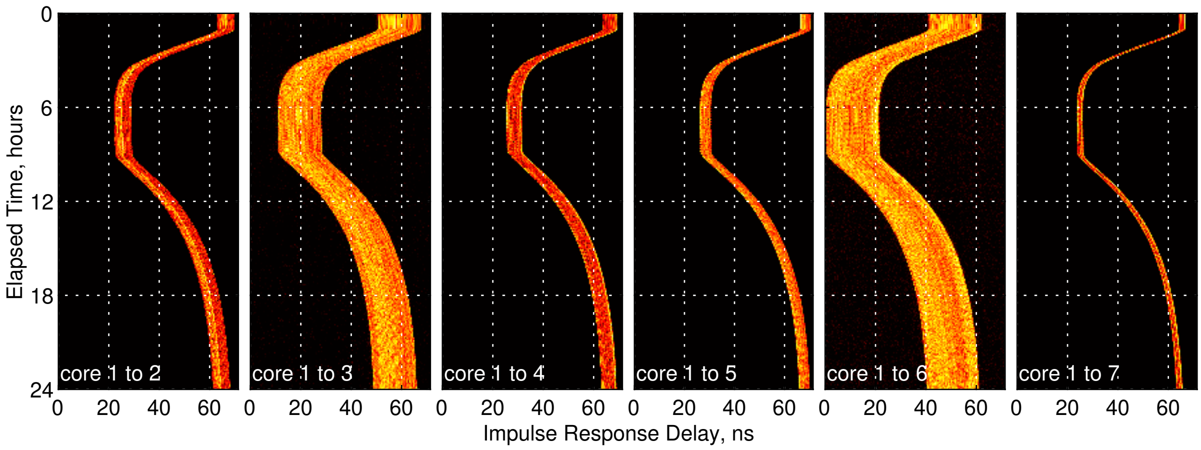

Fig. 4: Crosstalk impulse responses over time and temperature from the central core (core 1) to the outer cores (cores 2 to 7).

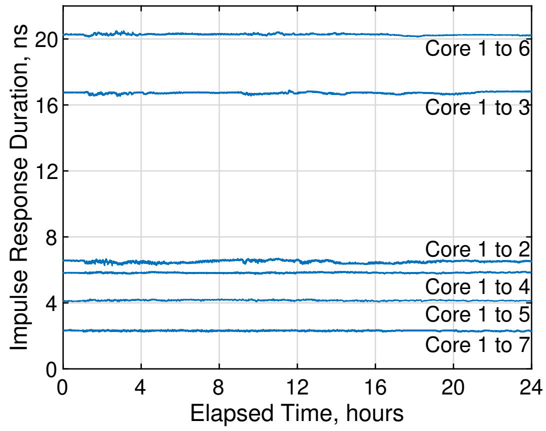

Fig. 5: Duration of the impulse response for the considered core pairs during the 24h measurement periods.

different cores as a result of bending, twisting and manufacturing process. These phenomena tend to increase the duration of the impulse response but not necessarily the skew between cores on a multi-span link. As the different segments of MCF may have opposing skew signs, the combined skew may be smaller than the total duration of the system memory length and corresponding impulse response. This can be observed from the impulse response for cores 1 and 7, shown in Fig. 2. In this case, the skews of the different fiber segments nearly cancel[15]. Nonetheless, the impulse response has a non-negligible duration of 2.3 ns. In contrast, the interaction between cores 1 and 6 has all three segments with the same skew sign, leading to an ICS around 21 ns[15], similar to the impulse response duration of 20.2 ns. The higher ICS can be explained by measurement error due to the patch cords in the fan in/out devices.

We varied the temperature in the thermal chamber as shown in Fig. 3. We kept a temperature of 22°C for one hour before raising it to 40°C. This required approximately 1 hour, after which the temperature was kept at 40°C for 2 hours and let to cool back down to 22°C for a period of approximately, 20 hours. This process was repeated for each considered pair of cores. Fig. 4 shows the magnitude of the impulse responses during the measurement period of 24 hours. It is shown that the relative position of the impulse responses varies by approximately 40 ns when increasing and decreasing the temperature of the thermal chamber. This variation is nearly the same for all cores, regardless of the duration of the corresponding impulse responses, similarly to the behavior observed in previous work[16]. From the results shown in Fig. 4, we computed the duration of the impulse responses during the measurement period, shown in Fig. 5. It is clear that the duration of the impulse responses tends to remain unchanged despite the temperature fluctuations and regardless of the significant change in propagation delay. However, we must stress that the temporal resolution of this experiment was limited to 20 ps. Hence fluctuations below that value would require higher sampling rates to detect. Furthermore, we note that the duration of the impulse response is not necessarily related to the ICS. Hence, they do not necessarily disagree with previous observation of temperature dependent ICS[9]. These observations may allow some insight on the behavior and interplay between MCF crosstalk and dynamic skew for future works.

Conclusions

In this work, we experimentally evaluated the dependence of the crosstalk impulse responses of a 7-core 53.7 km multi-core fiber on the temperature. It was shown that the propagation delay varies by more than 40 ps/km/°C. Nevertheless, the duration of the impulse responses and subsequent memory length of the system seems to remains relatively unchanged within the limits of the measurement technique.

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