Characterization of Phase Stability and Core-to-Core Delays in a Field-Deployed Uncoupled-Core Multi-Core Fiber Cable

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Abstract *We measure the relative core-core drifts of a 6.3 km installed multi-core fiber cable, reporting <420 fs of relative drift over 9 h for all core combinations. The corresponding frequency noise is shown to be around* 10^{-4} *and* $< 10^{-5}$*[Hz^2/Hz] at 1 Hz and 1 mHz, respectively.*

Introduction

Multi-core fibers (MCFs) are optical fibers with multiple cores sharing a common cladding[1]. The cores in an MCF are naturally expected to be much more correlated compared to parallel single-mode fibers (SMFs). If sufficiently correlated, this could enable new applications of MCFs. Examples of this include joint signal processing for phase[2],[3] and clock recovery[4] and exploiting the correlation for time-transfer[5]. To facilitate this, accurate characterization of deployed MCFs is vital to understand the degree of correlation and how it changes with time[6],[7].

Here we characterize field-deployed MCFs focusing on the relative changes/skew/phase between cores. Previous studies of core skew and phase stability[8],[9] had meters of fiber pigtails on the inputs and outputs which introduce large and uncorrelated phase shifts, skews, and polarization rotations caused by the birefringence in the pigtails. These effects are orders of magnitude larger than what we have found in our pigtail-less measurements of core-to-core stability. We use a combination of swept wavelength interferometry (SWI)[10],[11] and digital holography (DH)[12] to separate contributions from polarization effects on the relative phase change. We report core-to-core skew values below <420 fs over time scales of multiple hours and about 12 THz bandwidth. The skew is shown to be more than two orders of magnitude smaller than the change in fiber group delay over the same time period. We then use a free-space setup and digital holography to continuously measure the phase changes of all cores, showing frequency noise $\leq 10^{-4}$Hz^2/Hz for frequencies below 1 Hz.

Experimental Setup

The experimental setup is shown in Fig.1. The MCFs are deployed as part of the SDM test-bed in a tunnel under the city of L'Aquila, Italy[13]. The cable contains four strands of prototype 4-core uncoupled-core MCF, which was previously characterized and shown to have a cross-talk < -50 dB[14]. A cross-section image of the 4-core MCF and a picture of the deployed cable on its shelf are shown in Fig. 1(a). In most measurements[15], the noise caused by the fiber pigtails within the lab, dominate the noise introduced by the extremely quiet environment of the cable inside the tunnel. The SWI system[11] measures the complex Jones elements[16] and is outlined in Fig. 1(b). It used a tunable laser sweeping 12 THz covering the C- and L-bands at a rate of 2000 nm/s. Time-delays are used to resolve polarization and modes, enabling a complete coherent measurement of the transfer matrix (including all core-to-core coupling terms) in a single scan.

To measure the relative phase between cores without introducing any artifacts from pigtails, fan-in-out devices, and separate receivers, we used DH and measured all cores in parallel using an InGaAs camera operated at a frame-rate of 2.1 kS/s. The DH setup is shown in Fig. 1(c). We used a narrow linewidth laser (NKT X15) and split the light into two paths. One path, the reference path, was connected to a fan-in, sent through one core in one of the 4 strands of MCF, extracted using a second fan-out and used as our reference beam. In the signal path, a short free-space segment was used to expand the beam to evenly excite all 4 cores of the input connectorized MCF. At the output, a magnifying telescope resized the

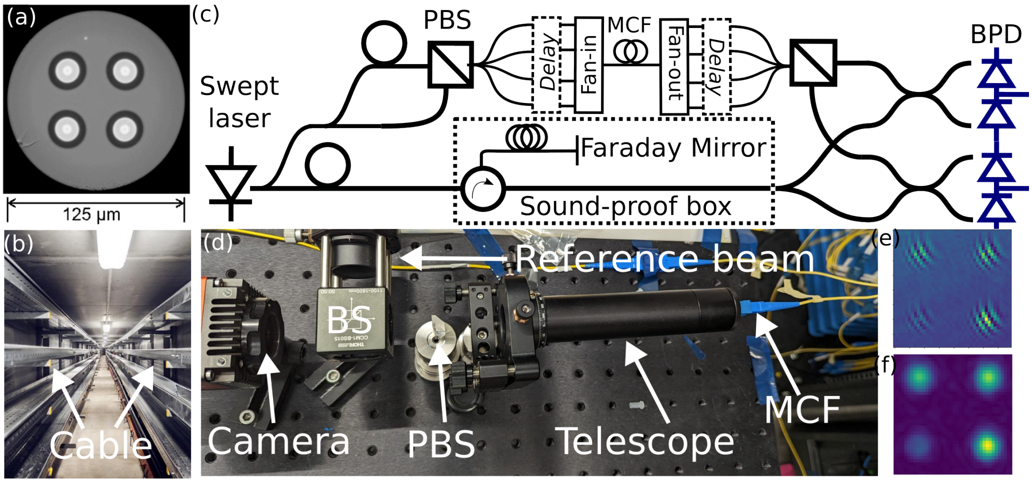

Fig. 1: (a) Cross-section of the uncoupled 4-core multi-core fiber. (b) Picture of the tunnel under the city of L'Aquila, Italy, in which the 6.3 km long fiber cable containing multiple strands of multi-core fiber is deployed on shelves. (c) Schematic of the swept wavelength interferometry system used to perform broadband characterization of the fiber. (d) Free-space digital holography receiver used to measure all four cores in parallel without the use of separate fiber pigtails. A narrow linewidth laser was split into two paths, one illuminating the input facet of the multi-core fiber under test and one generating the reference light, which was transmitted over a separate strand of fiber in the same cable. (e) Raw camera image of the received X-polarization showing the strong interference fringes. (f) Resulting image (magnitude of the complex values) after extracting the associated hologram.

output beam (containing all 4 cores spatially separated) onto a camera after polarization splitting horizontally and combining with a flat-phase reference. An example of a received ”raw” image with interference fringes clearly visible and the resulting intensity profile after extracting the hologram for the X-polarization are shown in Fig. 1.

Results

We first used the SWI system to coherently measure the frequency dependent Jones matrix, determining the linear transfer function, of each core of the 4-core fiber. Differential group delay (DGD) and PMD are calculated according to definitions in[10],[17]. The DGD values for each core, originating from polarization mode dispersion, are shown in Fig. 2. Over the 12 THz measured bandwidth the DGD varies up to 8 ps between the principle polarization states. Fig. 2 overlays data taken during nine hours every 5 minutes. The identical DGD proves that the fiber's birefringence does not change even at time-scales of hours. The DGD values observed also differs between cores, with some cores experiencing significantly larger DGDs than others. Note, these DGD values are a result of PMD strengths between 0.7 and 1.8 ps/$\sqrt{\text{km}}$ by MCF fabrication using early R&D stage process, these PMD values will be reduced by improving the MCF fabrication process. If only a single polarization is used to measure delay, this delay value would strongly depend on its polarization. The true core delay is the average of the DGD between both principle states of polarization. Using the polarization-resolved capabilities of the SWI system, we performed long-term (overnight) measurements to observe how the relative core-to-core phase changed, eliminating the effect of input polarization rotation induced DGD. The wavelength-averaged differential core-to-core skew averaged over the full measurement bandwidth is shown in Fig. 3(a). We observe very low skew values of $<$420 fs over the 9 h measurement window. From the skew measurements, a non-uniformity is observed, with some pairs showing stronger phase correlations. The fiber group delay (GD), over the same measurement period, is shown in Fig. 3(b). Compared to the sub-ps differential skew, we observe that the GD changes up to about 75 ps. This promising observation verifies the strong correlation for cores in MCFs.

To further investigate the phase stability between cores, we used the DH system which eliminates fan-ins and fan-outs directly measuring the 4-cores. We first compared the phase drift observed when using a 1$\times$4 splitter connected to a 4-core fan-in whose output was directly injected into the DH system with that of the 6.3 km MCF. A similar length reference fiber reduces laser phase noise artifacts in the measurements. The splitter-fan-in combination resulted in about 2 m of independent pigtails for each core. All fibers were taped down to a breadboard. The resulting phase-fluctuations over a 30 min measurement period are shown in Fig. 4(a) and (b) for the case of pigtails and 6.3 km MCF, respectively. Interestingly, despite the large length difference, we observe that the pigtails show more relative phase changes than the MCF. The cor-

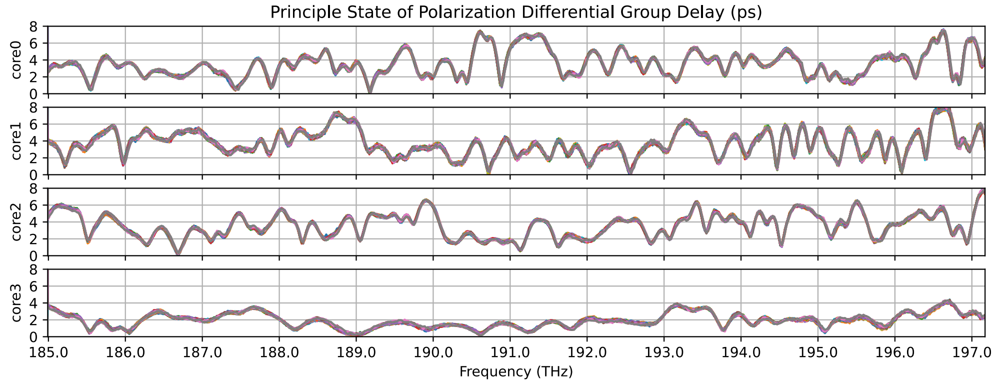

Fig. 2: Measurement of the differential group delay (DGD) for all four cores within the 6.3 km long 4-core multi-core fiber. The measurements show overlaid traces taken about 5 mins apart during a 9-hour time window, verifying that the observed DGD is stable over long time scales. However, the observed ps-level DGD implies that the observed propagation time will be highly sensitive to any change in input state-of-polarization.

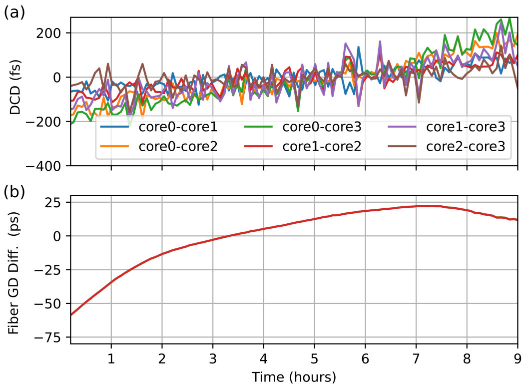

Fig. 3: (a) Differential core delay (DCD) averaged over the 12 THz measurement bandwidth during the 9 h long measurement. The observed core-to-core delay is changes with <420 fs. (b) The corresponding group delay change for the fiber. The change is about 2 orders of magnitude larger than the relative core-to-core delay of the multi-core fiber.

responding frequency noise spectra are shown in Fig. 4(c) and (d), respectively. The pigtail experiment is used to identify the noise floor of the system for frequencies above 10 Hz where we expect very little phase modulation from the fiber. Here we plot both the frequency noise of the relative phase drifts observed between cores (inputs of the fan/in) and the drift between the core and the reference phase. The drift with respect to the reference light is orders of magnitude larger than core-to-core drift, despite the reference fiber in this case being a second MCF inside the same tube, inside the same physical fiber cable. This is a direct indication of superior stability of cores within the same fiber. The core-to-core drift, however, is much lower, with values below 10^{-5} observed for frequencies <10 mHz. For low frequencies, we observe that 6 km of MCF outperforms 2 m of pigtails, despite the length difference being larger than three orders of magnitude. At higher frequencies, independent thermo-refractive noise (e.g., from the glass molecules jiggling because they have some temperature) accumulated in the long fibers become more present, giving raise to the increase in frequency noise.

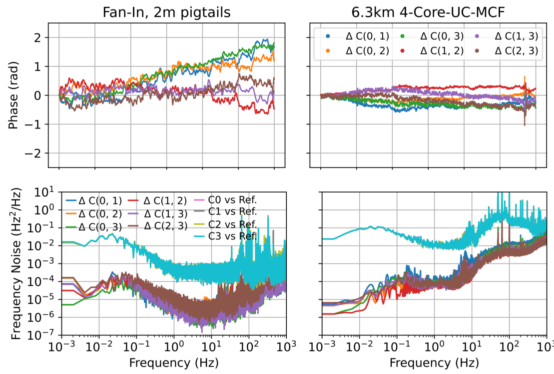

Fig. 4: (Top) Phase evolution and (Bottom) frequency noise spectrum, between all core-core combinations of a fan-in with 2m pigtails in the lab (left) and the 6.3 km multi-core fiber (right). A difference of 2 and 4 orders of magnitude is observed at a frequency of 1 Hz and 10 mHz, respectively.

Conclusion

We have investigated the absolute and relative delay properties between cores in field-deployed uncoupled-core multi-core fibers. Our results show that the relative core-to-core drifts are orders of magnitude smaller than the overall change in fiber group delay and the phase stability between the cores of a 6.3 km fiber is better than 2 m of co-located pigtails. We observe relative skew values of <420 fs over time scales of 9 h and frequency noise below 10^{-5} and $\approx 10^{-4}$ Hz^2/Hz for frequencies below 10 mHz and 1 Hz, respectively. Our results provide further insights and verification of unique multi-core fiber properties that could be explored for applications such as joint digital signal processing and transfer of stable light sources between remote locations.

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