Comparison of transfer matrix stability between a 110 km 7-core coupled-core multi-core fiber and single-mode fiber

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Abstract: We use dual-comb spectroscopy to compare the stability and wavelength dependence of mode coupling in a 110 km coupled multi-core and a regular single-mode fiber. Phase and intensity fluctuations are compared, revealing differences in coupling dynamics.

1. Introduction

In coupled-core multi-core fibers (CC-MCFs), the cores are placed at a critical core-to-core spacing to induce random coupling [1]. A strong random coupled fiber has favorable transmission characteristics such as shortened impulse response that reduces the digital signal processing (DSP) complexity, mitigation of fiber nonlinearities [2, 3], and reduction is mode dependent loss. The drawback to CC-MCF, is the coupling creates a multi-path interferometer scrambling information across all the cores. While real-time multiple-input-multiple-output (MIMO) DSP can be used to descramble the coupled modes [4], understanding the transfer matrix stability to external mechanical perturbations is critical to understand the tracking requirements and scaling possibilities for such DSP implementations [5, 6].

Here, we extend dual-comb spectroscopy [7], a popular technique in optical metrology, to simultaneously measure one row of the transfer matrix of a 7-core fiber at 10 wavelengths spaced at 35 GHz. The dual-comb technique mixes two phase coherent optical frequency combs with slightly different comb spacings (i.e., f and $f+\Delta f$) in a coherent receiver such that each comb line across the entire comb bandwidth is downconverted producing a RF comb with spacing of Δf that can be digitized using low speed ADCs with long recording times. One comb is used as a reference, and the other comb is transmitted over the fiber. The amplitude and phase of the $i-th$ downconverted comb lines contains the amplitude and phase of the transmitted comb at frequency $i \times f$. The bandwidth compression enables the use of lower-speed digitizers, allowing measurements over time scales of seconds compared to typical higher-speed real-time oscilloscopes. Dual-comb spectroscopy can be parallelized using an array of coherent receivers to simultaneously capture the spatial and spectral content of the transfer matrix. For a 7-core fiber with 14 spatial and polarization modes, traditional techniques to probe the transfer matrix at 10 well separated wavelengths would require 140 receivers, where dual-comb spectroscopy only requires 14 low speed receivers, one for each spatial mode.

We apply dual-comb spectroscopy to study the coupling dynamics of coupled-core fiber across 350-GHz spectral bandwidth. We split the probing comb and launch it simultaneously on 1 input core of a 7-core coupled-core fiber span and a reference standard single-mode fiber. Both spans were 110 km long. While direct comparison at steady-

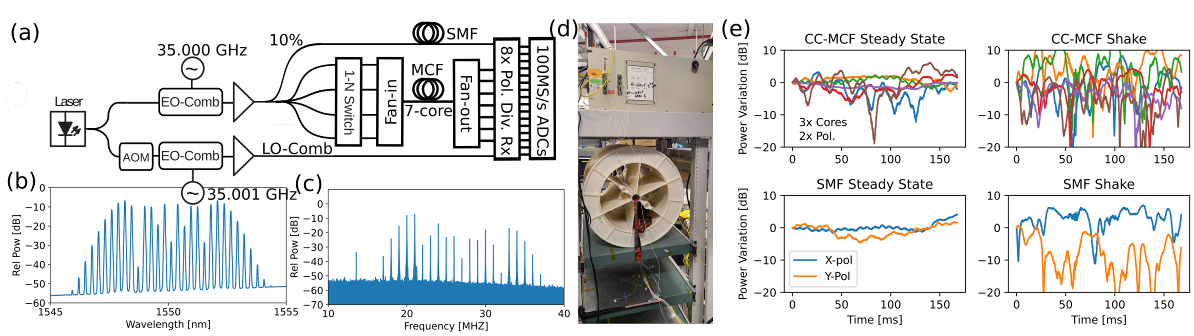

Fig. 1: (a) Experimental setup for dual-comb spectroscopy measurements of coupled-core multi-core fiber. Two frequency combs with 35.000 and 35.001 GHz line spacing, respectively, were generated using two phase modulators. One comb was then split and launched on one core of the coupled-core fiber and the single-mode fiber reference simultaneously. The output of both fibers were combined with the reference comb using 8 polarization-diverse optical hybrids and digitized using 16 balanced photodiodes followed by 16 100-MS/s analog-to-digital converters. (b) Spectrum of the generated frequency comb. (c) Example of digitized spectrum showing the downconverted RF comb. (d) Picture of the rack holding both fiber types. (e) Comparison of phase and intensity stability between the two fiber types (3 output CC-MCF cores and SMF) under steady-state and a moderate shaking event.

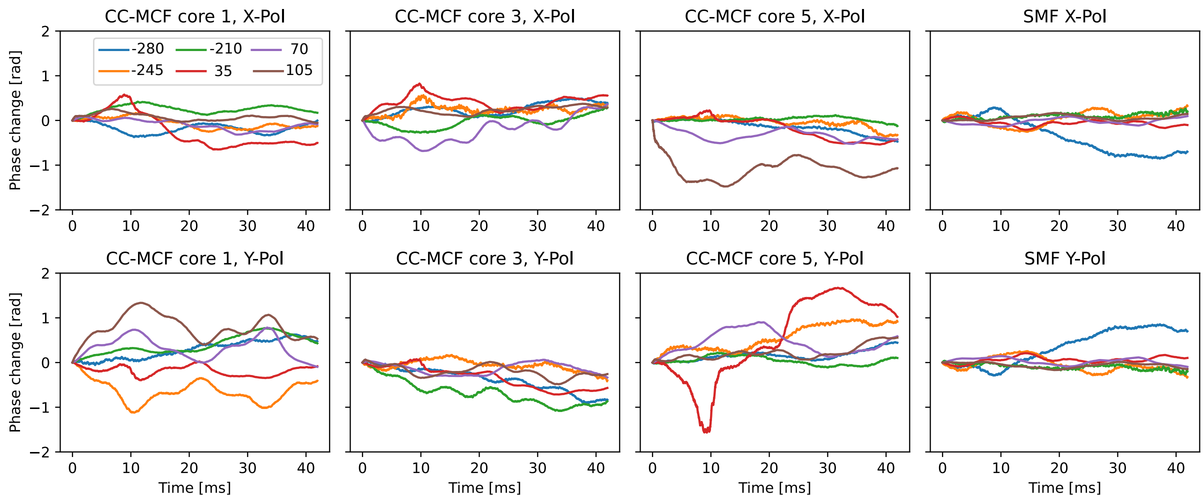

Fig. 2: Relative phase drift comparison between 3 output cores from 110 km coupled-core and SMF, for 6 different offset frequencies, under general lab conditions. Larger phase variations are observed for the coupled-core fiber compared to SMF and while similarities are seen between different outputs, no clear polarization grouping is observed. This is in direct contrast to the single-mode reference, showing a very strong similarity between the polarizations.

state shows that the coupled-core fiber transfer matrix elements are more sensitive to phase and intensity fluctuations, comparisons at moderate fiber shaking shows that both fiber show similar rate of change. The changes are on the order of ms, or slower, verifying that large-scale MIMO DSP can track these changes.

2. Experimental Setup

The experimental setup used is shown in Fig. 1(a). A Hz-level linewidth fiber laser (NKT BASIK) was divided into two paths and modulated using two overdriven phase modulators to generate the frequency combs. The RF signals were generated using two synthesizers synchronized to a common clock reference. The optical spectrum and resulting RF spectrum are shown in Fig. 1(b) and (c), respectively. The probing comb was amplified and split into two parts using a 90/10 coupler. The 90% output was connected via an optical switch to the 7-core CC-MCF fan-in device to enable sequential launch in the different cores. The 10% port was connected to the reference single-mode span. Both fiber spans had a length of 110 km. The SMF span was placed on top of the rack containing the CC-MCF, as shown in Fig. 1(d). This ensured that vibrations from the amplifier fans in the same rack propagated to both spans. The other comb was split eight times and eight polarization-diverse optical hybrids were then used to connect the output fibers from the 7-core fan-out and the final one was used to receive the SMF reference. In addition, as shown in Fig. 1, a 27-MHz acousto-optic modulator (AOM) was used to frequency shift the reference comb to ensure that the beat notes ended up at unique spectral positions. The 8 hybrid output signals were connected to balanced photodiodes (BPDs) and digitized using 8×16-bit 100 MS/s analog-to-digital converters. The ADC sampling clock was locked to the comb combs, ensuring full coherence. The ADC board was equipped with sufficient memory to store 3 s of measurement data. The post-processing consisted of frequency-domain-based line selection using a 250 kHz bandwidth digital filter.

3. Results

First, we compared the stability of the measured intensities for both the CC-MCF and SMF at the laser seed wavelength of 1550.12 nm, as shown in Fig. 1(e). All measurements are normalized so that the starting value is zero for all lines and cores. At steady-state, we observe larger intensity fluctuations for the CC-MCF as expected by the higher-dimensional interferometer formed by the coupling. Occasional deep fades reaching 20 dB for one channel are observed for the CC-MCF, in contrast to the SMF. We then shook the rack, achieving about 0.4G acceleration variations as measured by an accelerometer placed next to the CC-MCF spool. Interestingly, both fibers show deep fades (note that the launch state is single polarization). The fastest changes are observed at time scales of a few ms, as can be seen in Fig. 1. The maximum rate of change is also similar, showing that while the CC-MCF naturally has more elements that requires tracking, the rate of change is not that different from a regular SMF.

We then compared the phase evolution for multiple comb lines measured in parallel under steady-state condition, as shown in Fig. 2. The 6 selected frequency lines covered a total bandwidth of almost 400 GHz. An important observa-

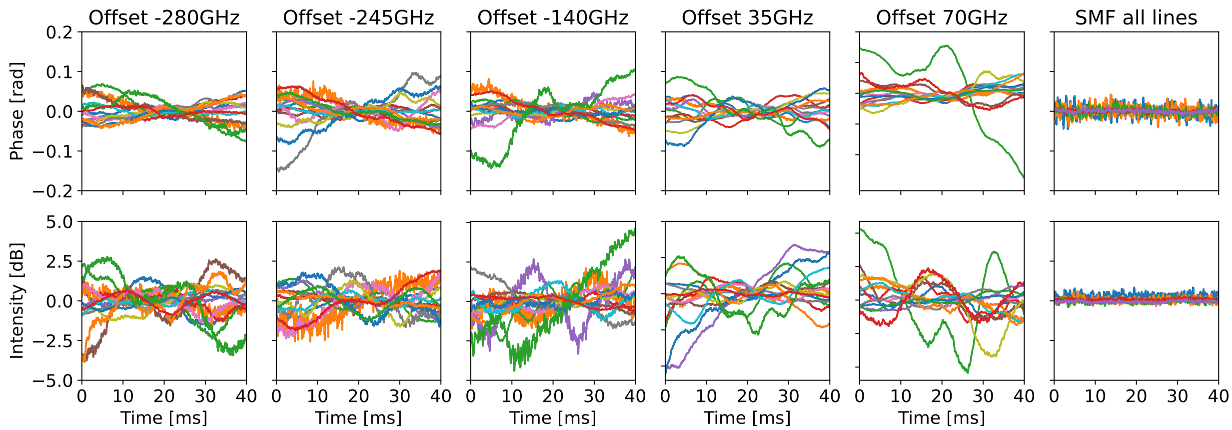

Fig. 3: Measured phase and intensity fluctuations from all 14 modes in the coupled-core fiber (both polarizations for all 7 cores) together with the 2 modes from a single-mode for 5 different comb lines with a total spacing of 350 GHz. Both the phase and intensity values are normalized to the average, highlighting the relative drifts under general lab conditions when the fiber is subject to slow thermal drifts and acoustic noise. Compared to the single-mode fiber, we observe a rapid decorrelation between the different wavelengths for the coupled-core fiber and the response looks random even between two consecutive lines (35 GHz spacing). At each frequency, we can observe some common signatures for a few lines, indicating weak grouping of polarizations in a core.

tion, especially important for designing MIMO DSP for CC-MCF transmission, is lack of similarities between polarizations for the CC-MCF case. For SMF, we observe changes that are close to identical (but inverted in Fig. 2) between both polarizations, indicating that most phase change have very little polarization dependence. For the CC-MCF, the concept of polarization mode fades out, and we observe general coupling terms that looks largely independent. Worth noticing though is that while the phase changes are slightly larger for CC-MCF, the fiber is still very stable and the changes are slow varying.

Finally, we compared both intensity and phase together for all outputs (7 cores and two polariztions for the CC-MCF and 2 polarizations for the SMF) as shown in Fig. 3. We measured 5 comb lines with a total frequency separation of 350 GHz. The measured phase and intensity for all outputs from the CC-MCF are shown in the first 5 columns of Fig. 3. Since the SMF only supports 2 polarization modes, all lines are plotted together. As expected, we observe larger variations in both phase and intensity for the CC-MCF compared to the SMF, from which hardly any variations are observed. In line with the results observed in Fig. 2, no clear frequency correlation is observed even between the closest spaced comb lines. Studying the results closely reveals occasional similarities, but the transfer matrix is in general fully scrambled, with a very narrow spectral autocorrelation between events. This is in strong contrast to SMF from which correlations over hundreds of GHz, or longer, is common for fiber lengths around 100 km. For the CC-MCF, we once again observe smooth and slow changes, happening over time scales of several milliseconds. While the rate of change is not likely to cause challenges for a real-time DSP implementation, the larger variations might require additional digital precision. Similarly, the strong frequency decorrelation might result in new considerations regarding the actual implementation of DSP, especially for high symbol rates approaching or exceeding 100 GHz.

In conclusion, we have used dual-comb spectroscopy to measure and compare the transfer matrix stability of a 110-km 7-core coupled-core multi-core fiber and a regular single-mode fiber. Our measurements show that while the coupled-core fiber naturally is more sensitive to environmental fluctuations compared to the single-mode fiber, the rate of change are slow. When shaking both fibers, similar deep-fades are observed for both fiber types and the rate of change is not significantly larger for the coupled-core fiber. Most importantly, no clear polarization structure is observed for the coupled-core fiber and the transfer function is strongly frequency dependent, decorrelating between two comb lines placed 35 GHz apart. Our results provide insights towards a more thorough understanding of coupled-core fibers and the stability of strongly coupled core structures to environmental perturbations.

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