Channel Dynamics in Few-Mode Fiber Transmission Under Mechanical Vibrations

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Abstract: We experimentally investigate the coupling dynamics of a three-mode fiber recirculating transmission link under the influence of controlled mechanical vibrations. The dynamics are found to be more prominent compared to similar measurements in single-mode fiber.

OCIS codes: 060.2330 Fiber optics communications, 060.2400 Fiber properties

1. Introduction

Space-division multiplexing (SDM) is a promising approach to increase the data-rates in optical fiber transmission systems [1]. Several fiber types have been proposed for SDM transmission, including coupled [2] and uncoupled [3] multi-core fibers (MCF), as well as few- and multi-mode fibers (FMFs and MMFs) [4,5]. When employing SDM fibers with multiple coupled spatial paths, higher order multiple-input / multiple-output (MIMO) processing is required to undo coupling between spatial channels, which is typically implemented as digital signal processing (DSP). While to date, transmission experiments with SDM fibers are limited to lab environments, where fibers are stored in stable conditions, deployed SDM fibers will be subject to various environmental influences, such as temperature changes, lightning strikes and mechanical vibrations. In current single-mode fiber (SMF) systems, receiver equalizers need to be frequently updated to account for such dynamic variations of the transmission channel [6]. The dynamics of a 4-core coupled-core transmission system have been studied in [7]. Here, we analyze the channel dynamics of a three-mode fiber transmission system that is subject to mechanical vibrations, introduced by a three-dimensional shaker. While we observed channel fluctuations in the FMF system, no dynamic effects were visible in a control experiment using SMF.

2. Experimental Setup

The experimental setup for the analysis of dynamic channel variations is shown in Fig. 1. An external cavity laser (ECL) with 10 kHz nominal linewidth and a wavelength of 1550 nm was modulated in a Mach-Zehnder modulator (MZM) with a 33.3 GHz sinusoidal tone to generate three laser lines for a high quality test-band. The three lines were split into odd- and even channels in a wavelength selective switch (WSS) and modulated in two independent single-polarization IQ-modulators (IQ-MOD). The modulators were driven by a four-channel digital-to analog converter (DAC), operating at 60 GSamples/s, and generating 30 GBaud root-raised cosine shaped quadrature phase shift keying (QPSK) signals with 0.01 roll-off. Polarization multiplexing (PDM) was emulated by splitting the signal, delaying one arm by 49 ns and combining the two signals in a polarization-beam combiner (PBC). Dummy channels were generated from four distributed feedback lasers (DFBs), spaced at 100 GHz around the test-band that were modulated in another MZM with a 33.3 GHz sinusoidal tone to generate 12 laser lines. Those were modulated by two IQ-MODs with 30 GBaud QPSK signals, generated by a second four-channel DAC, followed by a PDM stage and a dynamic gain equalizing filter (DGEF). Test- and dummy channels were combined using a WSS.

The signals were then split and send to two different recirculating loop setups. For the FMF transmission loop, the signal was split into three paths that were optically de-correlated in steps of 100 ns to emulate independent data for each spatial channel. Each signal was then sent to an independent loop setup, consisting of a 1x2 switch (SW), amplifiers, a variable optical attenuator (VOA) and a DGEF. The three signals were transmitted over the three modes of a 96 km three-mode fiber, described in [8]. Mode-multiplexing was achieved through photonic lantern fan-in / outs. Another loop setup with a similar length SMF was used for comparison. Both, FMF and SMF were placed inside the chamber of a three-dimensional X-Y-Z shaker (Screening Systems QRS-410T). The vibration strength was controlled

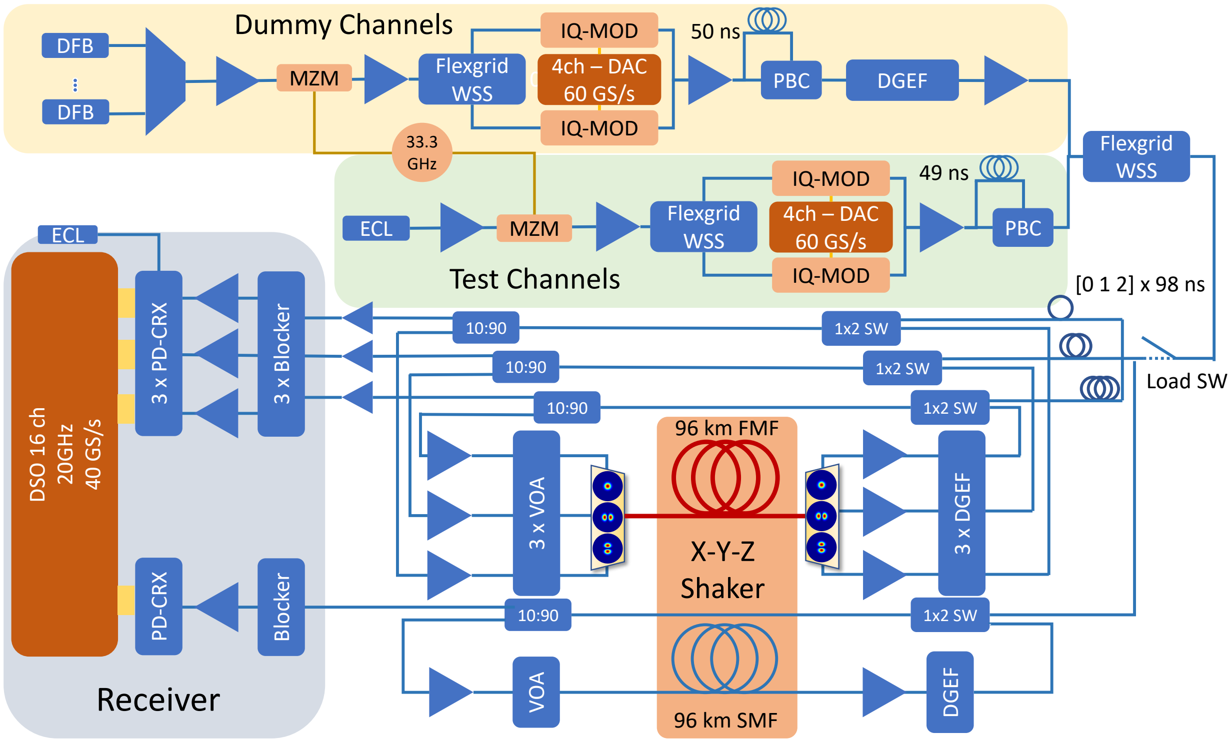

Fig. 1: Experimental setup to investigate channel dynamics a few-mode fiber transmission under influence of mechanical vibrations.

in levels between 0 Gms and 16 Gms, where the unit Gms represents the mean-square of the acceleration in reference to the acceleration of gravity over a frequency interval of 500 Hz. We note that at this point it is not clear how the vibration strength used in this experiment on a spooled fiber relates to perturbations that can observed in a deployed fiber.

The three outputs of the FMF loop and the SMF loop were received by polarization-diverse coherent receivers, where the signals were mixed with a 10 kHz ECL as local oscillator. The electrical signals were digitized in a 16-channel digital storage oscilloscope (DSO) at 40 GS/s sampling rate. Offline digital signal processing consisted of static chromatic dispersion compensation, a coarse frequency offset correction and a frequency domain 6×1 MIMO equalizer with 600 taps (2×1 for SMF) using a data-aided LMS update algorithm to extract the signal that was launched into the X-polarization of the fundamental mode. We analyzed the convergence behaviour of the equalizer for various settings of the equalizer and different strengths of mechanical vibrations, to asses the dynamic changes of the channel matrix, which is estimated by the MIMO equalizer.

3. Analysis and Discussion of Dynamic Channel Variations

Figure 2 shows the core results. All plots show the magnitude of the equalizer error of either the 6×1 equalizer for mode-demultiplexing or the 2×1 equalizer for polarization-demultiplexing of the first transmitted tributary (X-polarization of the fundamental mode), calculated in a data-aided mode after 2880 km distance. To cope with the limited number of samples that were stored in the DSO (corresponding to approx. $10\mu s$), we passed the received trace multiple times through the equalizer for better convergence. To improve visibility of the graphs, we show the equalizer error after convolution with a 1000 sample rectangular windowing function. Figure 2(a) shows the equalizer error considering a relatively small convergence parameter of $\mu = 5^{-7}$, 25 passes through the equalizer and without mechanical vibrations of the fiber. In this case, the equalizer converged to a stable solution. Figure 2(b) shows the equalizer error with the same equalizer settings but while applying vibrations at 16 Gms to the fiber. It can be seen that the equalizer converges slower for the first pass, while also not achieving a steady solution even after 25 passes. This indicates that the channel matrix changes faster than it can be tracked by the equalizer with the assumed settings.

We re-processed the traces using an equalizer with $\mu = 5^{-6}$ and 10 passes, with the results shown in Figs. 2(c) and (d). In absence of mechanical vibrations, the equalizer converged to a solution with same error as with with the previous equalizer settings. However, the trace that was recorded in the presence of 16 Gms shaking shows that the equalizer failed to converge to a steady solution, as the equalizer error increases towards the end of the trace.

Figures 2(e) and (f) show the equalizer errors when transmitting the data over SMF for (e) no mechanical vibrations

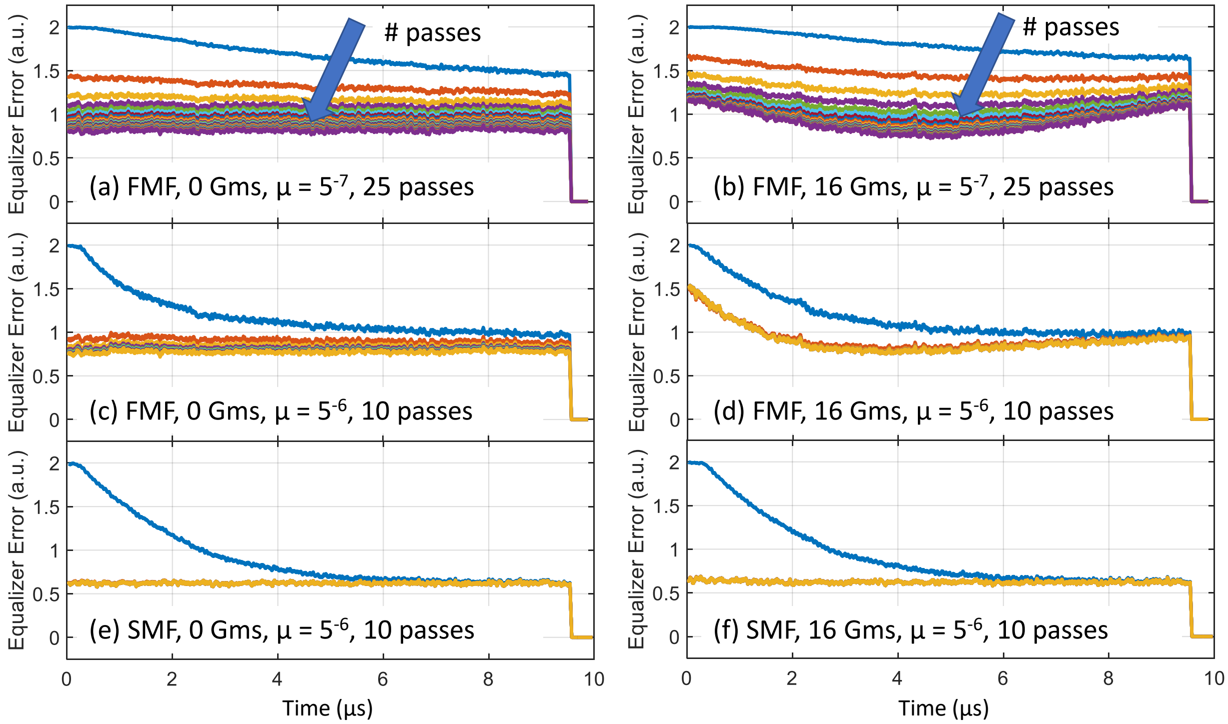

Fig. 2: Equalizer error along the recorded data-trace. Different colors represents different iterations of the data passing through the MIMO equalizer. Left plots without, right plots with application of mechanical vibrations. (a-d) different convergence parameters and number of passes after 2880 km few-mode fiber transmission. (e) and (f) equalizer error after 2880 km single-mode fiber transmission.

and (f) strong vibrations of 16 Gms. In both cases, the equalizer fully converges after the first pass with no visible influence of the mechanical shaking on the time-scale of the change of the channel matrix.

We note that there are other DSP methods that maybe more suitable to adopt to the faster channel dynamics in FMF such as recursive least squares (RLS) [9]. We also leave it for future work to extend this investigation towards a full Stokes-space analysis of the FMF system, while the main goal of this work was to analyze the equalizer convergence, being essential for an accurate Stokes analysis. Nevertheless, the present results indicate that the channel matrix changes on a faster time-scale in the FMF transmission system compared to a reference SMF transmission system.

4. Conclusion

We have investigated the convergence behavior and the dynamic equalizer error in few- and single-mode fiber transmission over more than 2800 km distance when applying severe mechanical vibrations to the transmission fiber. We have shown that the few-mode transmission channel changes on a time-scale of several μs when applying mechanical vibrations, while a reference single-mode fiber transmission system shows no impact of the vibrations of the same strength. This study highlights the importance of understanding the mode-coupling dynamics in few-mode fibers and their consequences for the implementation of robust and reliable real-time digital signal processing algorithms.

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