Modal Dynamics in Spatially Multiplexed Links

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Abstract: We investigate the vibration sensitivity of spatially multiplexed links by measuring the mode-coupling dynamics of a four-core coupled-core fiber and a reference single-mode fiber. We show that the speed of dynamics increases with mode count.

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1. Introduction

Coupled-core multi-core fibers (CC-MCFs) are strong candidates for use in ultra-long-haul mode-division-multiplexed (MDM) transmission systems because they possess favorable characteristics: low group delay spread which leads to reduced digital signal processing complexity, and both larger modal effective areas and random linear coupling which lead to enhanced tolerance of nonlinearities [1–3]. Recently, Hayashi et al. [3] demonstrated an optimized four-core multicore fiber (CC4) with an low modal dispersion of 3.1 ps/$\sqrt{\text{km}}$ and a low attenuation of only 0.158 dB/km. Ryf et al. [1] demonstrated that this CC4 fiber outperforms a commercially available single-mode fiber (SMF) with nominally the same core design for distances ranging from 500 km up to 10000 km using a recirculating loop transmission experiment. The temporal dynamics of mode coupling for CC-MCFs in the presence of environmental vibrations (i.e., how fast do modes couple) is still largely unstudied. Previous experiments [4] using a three-spatial-mode fiber have suggested that multimode systems change an order of magnitude faster than SMF systems. Recently, Choutagunta et al. [5, 6] proposed theoretical channel models to study the dynamic mode coupling behavior in multimode links by extending the Hinge model of SMFs [7]. Here, we experimentally compare the dynamics of CC4 fiber (eight spatial and polarization degrees of freedom) with a standard SMF (two polarization degrees of freedom) and show the CC4 channel is far more sensitive to vibrations than the SMF channel. Our experimental measurements qualitatively agree with our theoretical prediction that the increased dimensionality makes MDM systems more sensitive to vibrations. As MDM systems scale information capacity by transmitting in more modes [8], it is important to optimize adaptive equalizers so that they can track faster channel dynamics.

2. Theory: Dependence of MDM Channel Stability on Number of Modes

We first show mathematically that the MDM system dynamics inherently speed up when the number of modes is increased. The linear propagation of D spatial and polarization modes along the link can be described using coupled-mode theory by the partial differential equation $\partial \mathbf{E}(z)/\partial z = \mathbf{M}_{sh}(z)\mathbf{E}(z)$ where $\mathbf{E}(z)$ is a $D-$dimensional vector of modal complex baseband electric field amplitudes at spatial coordinate z, and $\mathbf{M}_{sh}(z)$ is a $D \times D$ skew-Hermitian matrix (in the absence of mode-dependent loss) that describes the infinitesimal rotation and phase accumulation of the modes due to random mode coupling. The elements of $\mathbf{M}_{sh}(z)$ are a function of an overlap integral of pairwise modal field patterns multiplied by a perturbation to the fiber's refractive index profile.

When the link is subjected to vibration, the refractive index profile of the fiber changes and $\mathbf{M}_{sh}(z)$ becomes time-varying. It can be modelled perturbatively as $\mathbf{M}_{sh}(t,z) = \mathbf{M}_{sh}(0,z) + \Delta\mathbf{M}_{pert}(t,z)$. The channel transfer matrix from z to $z+\Delta z$ is approximately $\exp\left(\mathbf{M}_{sh}(0,z)\Delta z + \Delta\mathbf{M}_{pert}(t,z)\Delta z\right)$ where $\exp(\cdot)$ denotes matrix exponentiation. To study the dynamics of this channel as the number of modes is increased, we define a normalized correlation metric as [6]

$$C(\kappa, D) = \mathbb{E}\left\{\frac{1}{D} \times \text{trace}\left[\exp\left(\mathbf{M}_{sh}\right)\exp\left(\mathbf{M}_{sh}^{H} + \sqrt{\kappa}\mathbf{M}_{pert}^{H}\right)\right]\right\},$$

where $\mathbb{E}\{\cdot\}$ is the expectation operator over random skew-Hermitian matrices $\mathbf{M}_{sh}$ and $\mathbf{M}_{pert}$ with element-wise independent complex Gaussian random variables of unit variance, and superscript H is the matrix Hermitian conjugate. The stability of a $D-$mode channel can be studied as a function of κ, which is the variance of the random perturbation to the mode coupling matrix, by averaging the correlation metric over a large ensemble of random matrix instances. Note that if mode-dependent loss is neglected and the channel matrices are assumed unitary, then from the properties of unitary matrices we get $C(0,D) = 1$. Our simulations also indicate that $C(\kappa_D, D) \approx 0$

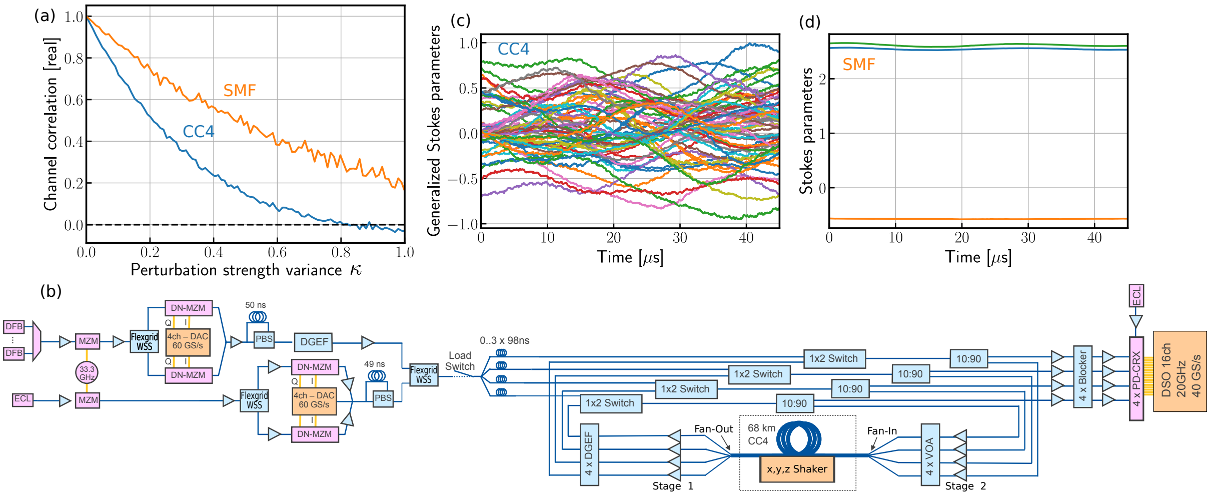

Fig. 1: (a) *Simulation:* Channel correlation of an example four-core coupled-core (CC4) fiber with $D = 8$ spatial and polarization modes and a single-mode fiber (SMF) with $D = 2$ modes obtained using Monte-Carlo simulations. The CC4 fiber channel decorrelates with less perturbation to its skew-Hermitian exponent than the SMF. (b) Experimental setup showing transmission fiber inside a three-axis shaker. (c) *Experiment:* CC4 fiber of length 68 km × 50 loops, all 63 generalized Stokes parameters for 4 GMS shake. (d) *Experiment:* SMF fiber of length 55 km × 50 loops, all three Stokes parameters for 4 GMS shake.

where $\kappa_D = 0.154 + 7.361/D - 18.255/D^2 + 34.101/D^3$ is the perturbation strength to decorrelate a $D \times D$ unitary matrix [6]. Fig. 1(a) suggests that when CC4 fiber (with $D = 8$) and a SMF (with $D = 2$) are disturbed by the same perturbation strength κ, the channel matrix corresponding to the CC4 fiber changes more than the corresponding SMF matrix. This behavior is corroborated experimentally, as shown in Figs. 1(c,d) and discussed below.

3. Coupled-Core Multicore Fiber and Measurement of Channel Dynamics

The CC4 fiber used in this experiment has four pure-silica cores with effective areas of 112 μm^2 within a standard 125 μm cladding. The core pitch of 20 μm was designed to provide adequate random mode coupling due to bends and twists, assuming a spun fiber. The fiber had a low modal dispersion of 3.14±0.17 ps/$\sqrt{\text{km}}$ over the C-band and attentuation of 0.158 dB/km, the lowest values ever reported for MDM transmission systems [3].

We slightly modified the transmission setup from a previous experiment [1], and a schematic of the modified setup is shown in Fig. 1(b). The transmitter produces 15 wavelength-division-multiplexed (WDM) channels spaced at 33.3 GHz and modulated at 30 GBaud. The signals are produced by eight independent high-speed digital-to-analog converters (DACs) operated at 60 GS/s, driving both in-phase and quadrature arms of four double-nested Mach-Zehnder modulators (DN-MZMs). We generated eight independent DeBruijn sequences of length 2^{16} to produce Nyquist-shaped QPSK transmission signals. We used external cavity lasers (ECLs) for the channel under test and as the receiver local oscillator. A polarization multiplexing emulation stage introduces a delay of 50 ns between the orthogonal polarizations to produce a polarization-multiplexed signal. The signal is then split into four paths, one for each core of the CC4, and decorrelated with delay fibers with a relative delay of around 100 ns. We used four solid-state 1×2 switches to inject the signals into the fourfold recirculating loop. We also added a load switch to improve the extinction ratio of the injected signal. The recirculating loops consisted of two spools of CC4 with a total length of 68 km, connected to four two-stage length-matched single-mode amplifiers and four dynamic gain equalizing filters (DGEFs) by using tapered couplers fan-in fan-out devices, fabricated to match the fiber cross section of the CC4. The CC4 spools were placed inside an evironmental chamber (Screening Systems QRS-410T) that produces random vibrations in each of the x, y and z axes. The strength of the vibration can be controlled by programming the shaker to discrete levels, ranging from 0 GMS (no shaking) to 8 GMS (high shaking), where the unit GMS is the mean square of the acceleration expressed in terms of acceleration of gravity g over a frequency range of 500 Hz. The transmitted signals are extracted from the loops using the 10% arm of four 10:90 couplers, and further amplified and filtered by programmable 150-GHz bandpass optical filters. They are then fed to four polarization-diverse coherent receivers (PD-CRXs).

The resulting 16 electrical signals are captured by a digital storage oscilloscope operating at a 40 GS/s sampling rate, and are processed off line by first up-sampling the signals to two samples-per-symbol, performing chromatic dispersion and frequency-offset compensation followed by timing identification and 8×8 MIMO processing, based on a frequency-domain equalizer with 1024 symbol-spaced taps. The initial convergence of the equalizer is obtained by using the data-aided least-mean-square (LMS) algorithm, whereas the constant-modulus algorithm is used afterwards. Carrier-phase recovery and bit-error-rate counting are performed and Q^2 factors are calculated. The equalizer step size was optimized empirically at each shake level to ensure sufficiently fast tracking and low

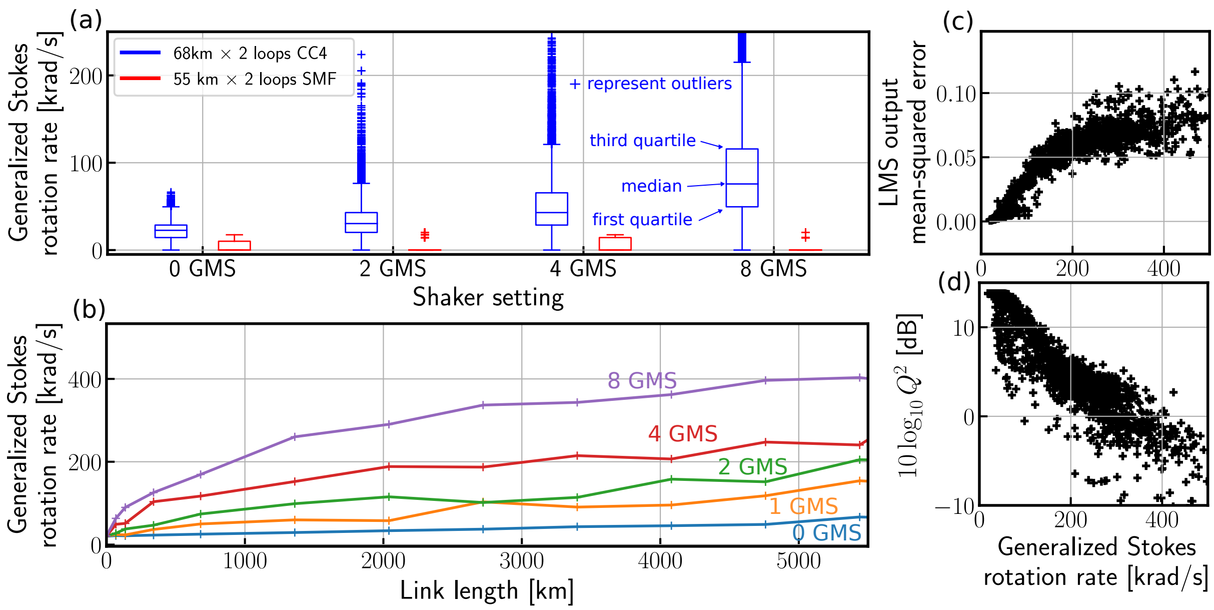

Fig. 2: (a) Distribution of the rotation rate of the generalized Stokes vector for a 68 km $\times$ 2 loop CC4 fiber and the rotation rate of the Stokes vector for a 55 km $\times$ 2 loop single-mode fiber, when both are perturbed by using a shaker operating at various shake strengths. (b) The rotation rate of the generalized Stokes vector for the CC4 fiber increases with the link distance. (c) The output instantaneous mean-squared error of the LMS equalizer is correlated with the instantaneous generalized Stokes rotation rate of the CC4 fiber. (d) Channel dynamics also impacts the received bit-error-rate and the derived Q^2 factors.

output error. The generalized Stokes parameters for SMF (3 parameters) and CC4 fiber (63 parameters) were extracted from the equalizer taps using the procedure described in [9], and the rotation rate of the generalized Stokes vector, which acts as a proxy for the channel rate of change, was computed by numerically differentiating the temporal evolution of the generalized Stokes parameters. The same measurement process was repeated for a 55 km spool of standard SMF using a single arm of the four-fold recirculating loop. Although the CC4 and SMF spools have different lengths and slightly different spooling radii, we believe their impact on the shaken transmission performance to be small.

4. Discussion and Conclusion

Fig. 2(a) suggests that the CC4 channel is far more sensitive to vibrations than the SMF channel. The rotation of the SMF's received Stokes vector on the 3-D Poincaré sphere was less than 3 krad/s for all shaker settings tested. This indicates that the shaker can induce faster polarization changes in SMFs than observed field measurements in terrestrial links (≈ 10 rad/s [10]) and in submarine links ($\approx 3.9 \times 10^{-2}$ rad/s [11]). In contrast, the CC4's 63-D generalized Stokes vector can rotate on the generalized Poincaré sphere at speeds exceeding 100 krad/s if the vibration in the shaker is strong enough. It is necessary to measure the dynamics of deployed coupled-core fibers to determine if the shaker settings are realistic. The speed of channel dynamics increases with the length link, as theorized in [5] and shown in Fig. 2(b). As seen from Figs. 2(c,d), extremely fast mode coupling can make tracking difficult for adaptive equalizers, leading to higher output errors and lower Q^2 factors. In summary, we have theoretically shown that MDM systems can change faster when the number of modes is increased, and have experimentally verified this behavior by comparing the dynamics of a CC4 fiber with a standard SMF. Alternately, adaptive equalizers, such as recursive least squares (RLS) [12], that are capable of faster tracking of channel dynamics at the expense of higher computational complexity, can be utilized.

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