On the Impact of Spatial Mode Dispersion for Mode-dependent Loss Estimation and Mitigation in Coupled-core MCF Links

Meng Mao[1], Bin Chen[2,*], Rendong Xu[3], Lin Sun[1,*], Junjie Xiong[4], Lin Ma[4], Gangxiang Shen[1] and Gordon Ning Liu[1]

[1] *School of Electronic and Information Engineering, Soochow University, Suzhou, Jiangsu 215006, China*
[2] *School of Computer Science and Information Engineering, Hefei University of Technology, Hefei, Anhui 230009, China*
[3] *Ocean College, Zhejiang University, Zhoushan, Zhejiang 316004, China*
[4] *State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China*

*linsun@suda.edu.cn *bin.chen@hfut.edu.cn

Abstract: Impact of SMD on MDL estimation and mitigation in CC-MCF links is theoretically investigated. SMD below 10 ps/km is mandatory to ensure the efficient MDL mitigation in 1000-km CC-MCF links.

1. Introduction

Motivated by the escalating demand for high-capacity data communication, the optical space division multiplexing (SDM) is promising to further boost the transmission capacity on the basis of single mode fibers (SMF) [1]. Recently, there have been some arguments about choosing suitable SDM strategies in the terrestrial and submarine transmissions for industrial considerations, like whether using the ribbon of multiple SMFs, multicore fibers (MCF) or few mode fibers (FMF) [2]. Notably, the intuitive advantages of MCFs and FMFs over the SMFs ribbon solution are the much higher spatial multiplicity with a certain cable size. At the same time, researches on the MCFs transmissions are gradually converging to those studies on the standard or even smaller-sized fibers with the cladding diameter below 125 μm [3]. Within the limited cladding area, the high-level inter-core crosstalk (IC-XT) is unavoidable to pursue the higher spatial multiplicity. In addition to the spatial density advantage, the coupled-core MCFs (CC-MCF) also have the merits of lower spatial mode dispersion (SMD) and fiber nonlinearity penalty due to the random mode coupling between cores [4]. However, there are two fundamental challenges for realizing the long-haul CC-MCF links: SMD and mode-dependent loss (MDL). The state of the art reported a record-low SMD value of CC-MCF is 3.14 ps/$\sqrt{\text{km}}$ [5], markedly surpassing the SMD of SMF, which is mere 0.1 ps/$\sqrt{\text{km}}$. The primary impact of SMD is degrading the performances of MIMO-DSP at the receivers [6]. MDL caused by multi-core erbium-doped fiber amplifier (EDFA) seriously constrains the transmission distance [7]. Previous measurements have shown an MDL of 2-3 dB of a 7-core coupled-core C-band EDFA [8].

To our best knowledge, we theoretically investigate the impact of SMD on MDL estimation and mitigation performances in CC-MCF links for the first time. The end-to-end MDL is estimated by the inverse matrix of MIMO taps (8×8) trained by the least mean square (LMS) algorithm. We observe that the SMD more than 10 ps/km increases the estimation error of MDL through this approach. Moreover, we apply space-time coding (STC) to mitigate MDL and demonstrate that an overall Q factor improvement can be achieved when SMD coefficient is below 10 ps/km.

2. Modeling of CC-MCF links with MDL estimation and mitigation

In CC-MCF links, for the optical field transmitted within one core which contains two polarization states, the propagation over the longitudinal coordinate and time with the coupling from other cores can be described by coupled nonlinear Schrödinger equation (CNSE). The CNSE is solved through the split-step Fourier method (SSFM), employing a fine step size that should be smaller than the coupling length L_c [4]. To validate the reliability of SMD and IC-XT settings in the conducted CC-MCF links, self-consistency verifications with SMD and IC-XT have been performed [4].

For the long-haul CC-MCF links, accurate estimation of MDL is crucial as it leads to a non-unitary channel transfer matrix that can limit the transmission performance. MDL can be characterized by two approaches: the peak-to-peak MDL and the root-mean-square (RMS) MDL. In this paper, we focus on RMS MDL because it has greater utility than peak-to-peak MDL in CC-MCF links [9]. The RMS MDL of a link can be given by $\sigma_{\text{mdl}} = \xi\sqrt{1+\xi^2/(12(1-\text{D}^{-2}))}$ and $\xi = \sigma_{\text{g}}\sqrt{\text{K}}$, where D is the number of modes, σ_{g} is the amplifier's MDL standard deviation and K is the span number [10]. The RMS MDL is expressed in units of the logarithm of power gain, which can be converted to decibels by multiplying by the coefficient $\gamma = 10/\ln 10 \approx 4.34$ [11]. The MDL of a link can be estimated from the eigenvalues of $\mathbf{H}\mathbf{H}^H$, where $\mathbf{H}$ is the channel transmission matrix and $(.)^H$ denotes the Hermitian transpose operator [10].

To alleviate the impact of MDL, the STC method is employed to distribute the power of each symbol across all modes. If the original symbol sequence vector is presented as $\boldsymbol{s}(t) = [s_1(t), s_2(t), ..., s_N(t)]^{\mathrm{T}}$, the formula of STC can be given by: $\boldsymbol{x}(t) = \frac{1}{\sqrt{N}} H_N \boldsymbol{s}(t)$, where H_N is the Hadamard matrix with the order of N. The transmitted symbol sequence vector $\mathbf{y}(t)$ is expressed as $\mathbf{y}(t) = [x_1(t), x_2(t-t_2), ..., x_N(t-t_N)]^{\mathrm{T}}$ [12]. In this work, N is set to 8 which corresponds to the mode number.

Fig. 1 depicts a multiple-span CC-MCF link with MDL estimation and mitigation. At the transmitter, symbols are modulated into quadrature phase keying (QPSK) format and then coded by STC. Afterwards, they are transmitted through a nonlinear optical channel. This channel consists of K spans of optical fibers, each of them followed by a multi-core EDFA. Different cores in a multi-core EDFA can couple and interact with each other in different ways, leading to MDL. At the receiver, after chromatic dispersion compensation (CDC) and LMS, MDL values are estimated from the inverse matrix of MIMO taps $\mathbf{W}$ (8×8) trained by LMS. Then frequency offset compensation (FOC), carrier phase estimation (CPE) and QAM demodulation are carried out.

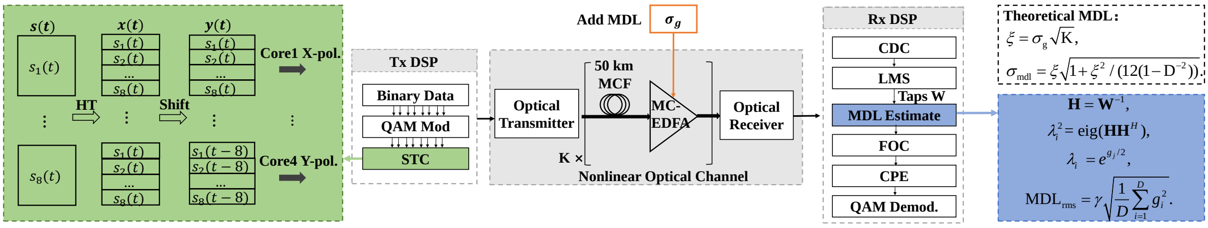

Fig. 1. The considered system of the CC-MCF links with MDL estimation and mitigation.

3. Results

Simulations of 50-Gbaud dual polarization QPSK transmission over 50-km coupled 4-core fiber spans have been conducted. The characteristics of the fiber, including fiber attenuation, dispersion coefficient and nonlinear coefficient, are set at 0.16 dB/km, 16 ps/nm/km and 0.81 W/km. Theoretical MDL is set at 0.7 dB per span. Fig. 2(a) presents the estimated MDL and theoretical MDL as functions of the transmission distance with L_c at 100 m. It can be observed that the RMS MDL values estimated from MIMO taps well align with the theoretical values, affirming the precision of estimation. We further assess the impact of SMD on MDL estimation performance in 1000-km CC-MCF links at different L_c, as depicted in Fig. 2(b). Note that the SMD coefficient is expressed in "ps/$\sqrt{\mathrm{km}}$" as the unit in CC-MCF links. However, "ps/km" is used in this work due to the fact that the transmission model is based on CNSE and utilizes the SSFM for solving. As shown in Fig. 2(b), when the SMD coefficient is small, the RMS MDL values are almost consistent with the theoretical values at different L_c. With the SMD coefficient increasing, the precision of estimation degrades. This is because the RMS MDL values are estimated from MIMO taps and the precision of estimation depends on MIMO-DSP performance. When the SMD coefficient increases in CC-MCF links, the inter-core skew in the optical paths of each core increases the complexity of MIMO-DSP and reduces the estimation precision. In the strong coupled MCF ($Lc = 100$ m), a maximum SMD coefficient of 10 ps/km can be tolerated in 1000-km CC-MCF links. The strong coupling among cores can suppress the accumulation of SMD, which is crucial to reduce the computational complexity of MIMO-DSP [5]. As a result, when L_c decreases, indicating a stronger coupling, the maximum tolerated SMD coefficient becomes larger and the impact of SMD on MDL estimation becomes less obvious.

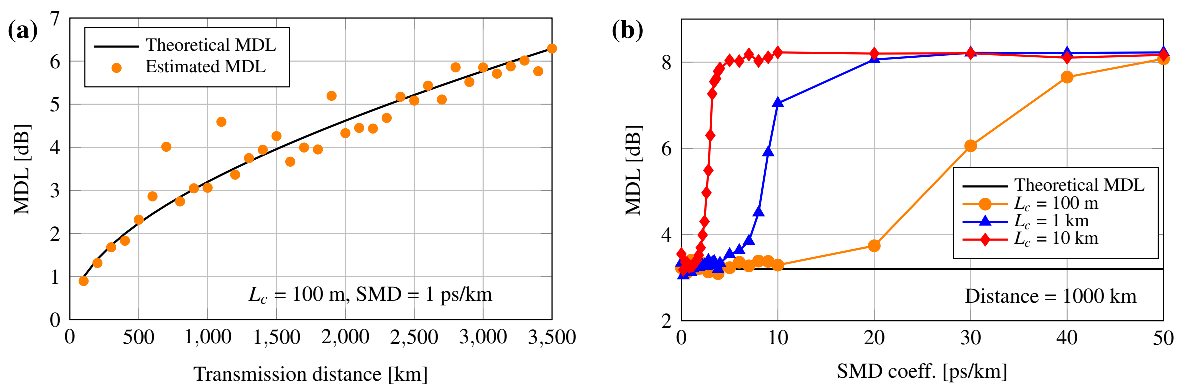

Fig. 2. (a) Estimated MDL and theoretical MDL with L_c = 100 m and SMD = 1 ps/km. (b) Estimated MDL vs. SMD with different L_c in 1000-km CC-MCF links.

To deal with the MDL issue, STC method is employed in CC-MCF links. Fig. 3(a) depicts the mean Q factor as a function of transmission distance with and without STC with L_c at 100 m. Due to the randomness of MDL, we perform 20 times of simulations then calculate the mean Q factors over all cores. In the conventional method, the mean Q factors over all cores decrease as transmission distance increases. On the contrary, the mean Q factors remain relatively stable with STC. The STC method can achieve an overall Q factor improvement by balancing the performance of four-core signals in CC-MCF links. We observe that the employment of the STC method has a more noticeable effect on MDL mitigation in longer transmissions. In 1000-km CC-MCF links, the STC method can obtain 7-dB gain in Q factor. In the insets (i) and (ii), the constellations with and without STC demonstrate that there are some differences in signal performances in the conventional method but the performances are almost consistent with STC.

We simulate mean Q factors vs. SMD over 1000-km transmission with and without STC when L_c is 100 m and different tap length conditions of MIMO-DSP are also considered in Fig. 3(b). When the tap length is 31, the employment of the STC method achieves higher Q factors when the SMD coefficient is below 10 ps/km, indicating that it has a notable effect on mitigating MDL. Conversely, when the SMD coefficient is over 10 ps/km, Q factors with the STC method are lower. Moreover, the maximum tolerated SMD coefficient becomes larger as the tap length increases, which indicates that STC increases the requirement for longer-tap MIMO-DSP, leading to lower Q factors. Based on the above results, using the STC method in MDL mitigation is suitable for low SMD situations in CC-MCF links due to the limited tap number of MIMO-DSP.

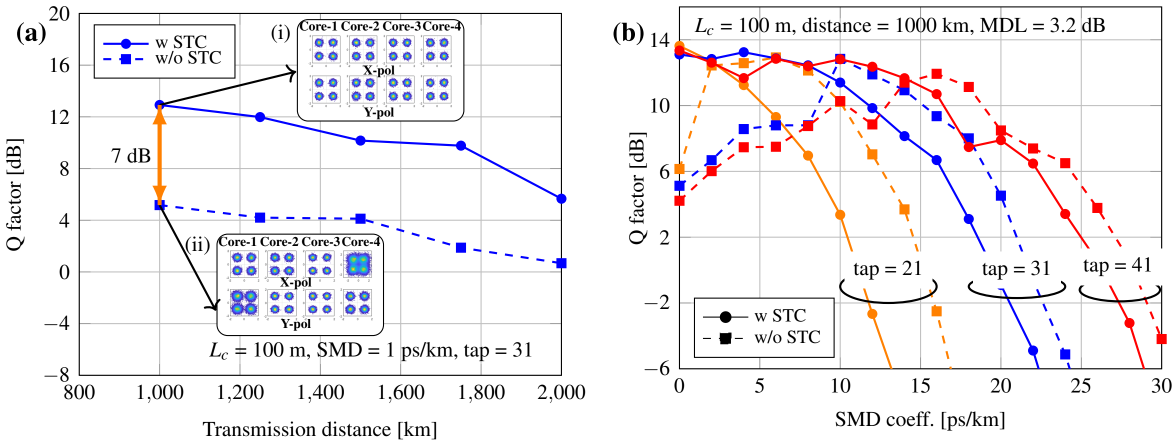

Fig. 3. (a) Q factor vs. transmission distance. Insets: (i) constellations with STC, (ii) constellations without STC. (b) Q factor vs. SMD with and without STC at different tap lengths.

4. Conclusion

We for the first time investigate the estimation and mitigation performances of MDL in CC-MCF links while also exploring the impact of SMD. Simulation results indicate that the MDL estimation and mitigation performances highly rely on the SMD. Typically, a maximum SMD coefficient of 10 ps/km can be tolerated by using 31 taps 8×8 MIMO-DSP in 1000-km CC-MCF links with L_c at 100 m. Additionally, we demonstrate that the application of STC effectively mitigates MDL and achieves an overall Q factor improvement when SMD coefficient is below 10 ps/km.

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