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Analysis of Few-Mode Multi-Core Fiber Splice Behavior Using an Optical Vector Network Analyzer

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Abstract *The behavior of splices in a 3-mode 36-core fiber is analyzed using optical vector network analysis. Time-domain response analysis confirms splices may cause significant mode-mixing, while frequency-domain analysis shows splices may affect system level mode-dependent loss both positively and negatively.*

Introduction

The introduction of space division multiplexing (SDM) using fibers with multiple cores and/or supporting multiple modes has allowed the capacity of optical communication systems to overcome the limit of conventional single mode fibers of around 100 Tbit/s and reach capacities in the Pbit/s range[1,2]. Few-mode multi-core fibers (FM-MCF), combining the use of multiple cores and modes, have driven the number of spatial channels above 100[2], at the cost of requiring multiple-input multiple-output (MIMO) equalization to reverse the mode-mixing taking place at (de-)multiplexers, at fiber splice points[2–4] and along the fiber.

The performance of the MIMO equalization—and hence the achievable system capacity—is, among other impairments, limited by mode-dependent loss (MDL) in the system[3]. Fiber splices between FMFs (and in particular for FM-MCFs) not only introduce insertion loss (IL), but also mode mixing and potentially MDL[5,6]. While splices may severely degrade system performance due to their IL and additional MDL[5], their mode mixing behavior may potentially reduce overall system MDL[5], to the point where artificial introduction of splices was considered for reach increase in FMF transmission systems[6]. As a practical system will feature a splice every 1–2 km, careful characterization of such splices is required to successfully model SDM systems based on FMFs and FM-MCFs.

In this paper, we experimentally investigate the impact of splices in a 36-core 3-mode FM-MCF using a spatially-diverse optical vector network analyzer (SDM-OVNA). The measurement is performed in a reflective manner, using a 3D waveguide spatial multiplexer with 36 photonic lanterns coupling to the 36 MCF fiber cores of a short FM-MCF pigtail which is further spliced to pieces of FM-MCF. The splices are found to significantly alter the complex transfer function of the system, introducing additional IL ranging from 0.01 dB to 1.99 dB for the different cores, changing the wavelength averaged sytem MDL by −1.2 dB to 2.8 dB and significantly altering its wavelength dependent profile. The presented results help to improve the modeling of SDM transmission systems based on FM-MCF, by including the effects of FMF splices.

Splice Characterization Using a Spatially-Diverse Optical Vector Network Analyzer

The analysis of splices between FM-MCFs was performed with an SDM-OVNA based on swept-wavelength interferometry[7], allowing measurement of the full complex transfer function $H(\omega)$ of a multiport SDM system. The SDM-OVNA setup, shown in Fig. 1, uses a continuously swept tunable laser source (TLS), followed by an interferometer including the device under test (DUT) in one of its arms, to iteratively measure the full 6×6 transfer matrix for each of the 36 cores. The TLS signal was split and recombined in a polarization beam combiner to ensure polarization diversity and split onto the different ports of the DUT. The reflections from the cleaved end of the FM-MCF were separated by optical circulators, combined and together with the reference arm of the interferometer fed to a polarization diverse receiver; the resulting interference fringes were stored on a digital sampling oscilloscope. An additional reference interferometer allowed for compensation of sweep frequency non-linearities[4,7].

The fiber delays at the polarization multiplexer (τ_{P}) and before and after the ports of the DUT (τ_1 to τ_6) separate the M^2 different components $h_{ij}(t)$ of the time-domain transfer matrix in the

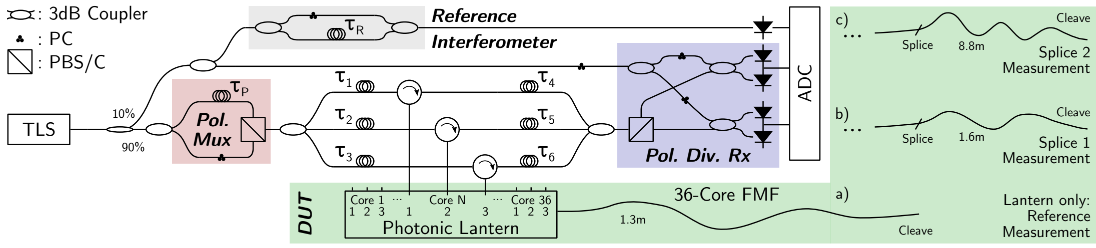

Fig. 1: SDM-OVNA setup and different measurement scenarios: a) photonic lantern and 1.3 m 3-mode MCF, b) photonic lantern and 1.3+1.6 m fiber with splice, c) photonic lantern and 1.3+8.8 m fiber with splice. TLS: continuously swept tunable laser, PC: polarization controller, PBS/C: polarization beam splitter/combiner, ADC: analog to digital converter.

inverse Fourier transform of the recorded interferograms, allowing easy extraction by temporal windowing. The separate Fourier transforms of the $h_{ij}(t)$ are the components $H_{ij}(\omega)$ of the $M \times M$ complex transfer function $H(\omega)$. Singular value decomposition of $H(\omega)$ gives the M singular values $\lambda_i(\omega)$ of the complex transfer function, from which IL and MDL are derived as: $IL(\omega) = \sum_{i=1}^{M} \lambda_i^2(\omega)/M$ and $MDL(\omega) = \max_{0<i\leq M}(\lambda_i^2(\omega))/\min_{0<i\leq M}(\lambda_i^2(\omega))$.

Two splices were introduced between the PL pigtail and two pieces of FM-MCF of 1.6 m and 8.8 m length respectively, to analyze the complex transfer function of the resulting reflective systems and to compare them to the transfer function of the pigtailed photonic lantern (PL). This comparison allows deriving characteristics of the splice, using the difference in wavelength-averaged IL and MDL as well as the ratio of the variance of MDL over wavelength as indicators of splice quality and impact.

Measured FM-MCF Splice Characteristics

Measurement of the system transfer characteristics gives a 6×6 time-domain response matrix for each core, from which by means of Fourier transformation and singular value decomposition the IL and MDL over wavelength can be derived as previously discussed. Two exemplary time-domain response matrices and corresponding IL and MDL are shown in Fig. 2. Detailed analysis of the time-domain responses allows drawing conclusions about mode coupling at different points along the system, including at the splice. Comparison of IL and MDL for the system in presence and absence of a splice allows determining splice quality and splice behavior.

Cores 6 and 33 of splice two were chosen for display in Fig. 2 a) and b) as they show significantly different behavior both in their time-domain response and their IL and MDL profiles. The time domain response of core 6 in Fig. 2 a) shows three clearly separated single peaks, where the approximately 145 ps separation between the outer peaks correspond to the accumulated differential mode delay (DMD) of passing through the 1.3+8.8 m of FM-MCF—which is known to have a DMD of around 7 ps/m[2]—in forward and backward direction. The presence of the central peak thus indicates strong mode-mixing to occur at the cleaved fiber end.

Core 33 on the opposite shows three groups of three closely spaced peaks, indicating that additional mode-coupling must take place. This is found to be mode coupling at the splice, causing peaks located close to the main peaks as the difference in accumulated DMD is equivalent to the DMD of a single pass through the 1.6 m FM-MCF between splice and PL, i.e. about 9.1 ps—which is in good correspondence with the observed peak spacing. While the shown cores represent the extremes, i.e. either practically zero mode-mixing or very strong mode mixing, the remaining cores show varying levels of mode mixing with no overall tendency to either extreme.

The behavior of cores 6 and 33 is further different in IL and MDL, as further shown in Fig. 2, with core 6 showing a nearly flat IL across wavelength and only small variations in MDL, while core 33 shows significant variations of MDL; the observed ringing, especially obvious on the IL of core 33, is due to the temporal windowing process. It should be noted that the presented IL and MDL values have been divided by two to account for the double-pass nature of the reflective measurement and thus represent the actual IL and MDL of the system.

Comparison of the IL and MDL between the system with and without the splice allows deriving the IL of the splice and its impact on MDL. To this end the differences in wavelength averaged IL are shown across a schematic plot of the fiber cross section on the left hand side of Fig. 3 for two different splices, where splice 1 is between the 1.3 m FM-MCF pigtail of the PL and a 1.6 m long piece of FM-MCF, while for the second splice the first splice is removed and a piece of 8.8 m of FM-MCF spliced to the pigtail.

Comparison of $\Delta\overline{IL}$ of the splices shows splice 2 to be of significantly better quality, with <0.5 dB IL, except for four isolated cores with IL up to 1.8 dB, potentially due to cleave imperfections,

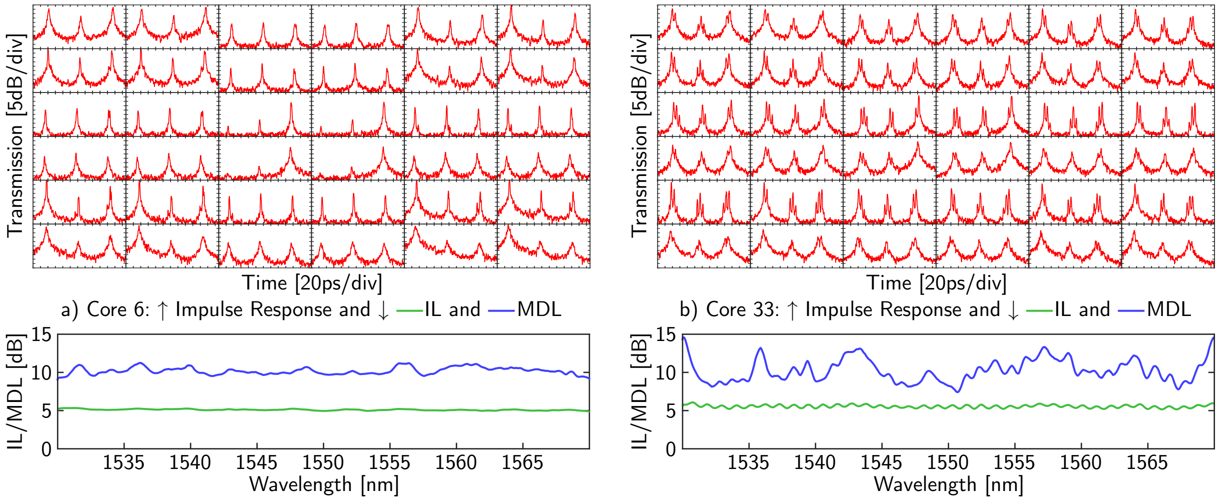

Fig. 2: Impulse responses and IL and MDL over wavelength for cores 6 and 33 for the system with PL and 1.3+8.8 m FM-MCF.

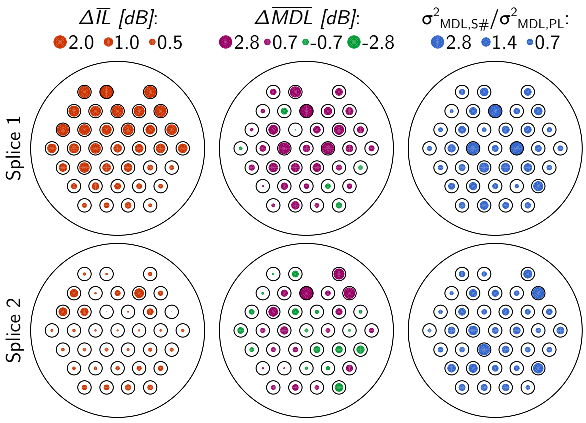

Fig. 3: Indicators for splice quality and impact for two splices of 36-core FM-MCF plotted over the fiber cross-section. $\Delta\overline{IL}$ and $\Delta\overline{MDL}$: difference in wavelength averaged IL and MDL, $\sigma^2_{\mathrm{MDL,S\#}}/\sigma^2_{\mathrm{MDL,PL}}$: ratio of MDL variance over wavelength between system with and without splice.

core displacements or micro-bubbles enclosed in the splice. Splice 1 on the other hand shows overall much higher IL with only the bottom right section of the fiber staying below 0.5 dB IL.

The middle and right parts of Fig. 3 show the difference in mean system MDL and the ratio between variances of MDL caused by the two splices respectively. While these confirm that both system MDL and its variance over wavelength can be reduced by a splice, for the majority of cores MDL increases, with an average increase of 0.8 dB across all cores in splice 1 and 0.2 dB in splice 2. The average impact on MDL variance however is found to be small, with average ratios of 1.0 for splice 1 and 0.9 for splice 2. It should be noted that a decrease in system MDL is connected to mode mixing in the splice and does not indicate gain in the splice.

Overall, these results confirm that splices in FMFs have significant impact on MDL behavior, especially in the case of FM-MCFs, where larger core offsets are unavoidable and thus differences in behavior across cores may be significant.

Conclusions

In this paper the behavior of splices between FM-MCFs has been investigated using optical vector analysis, analyzing splice impact both based on the system time-domain response and the changes in IL and MDL caused by the inclusion of a splice. The results show significant mode-mixing may occur at a splice and splices can significantly alter MDL behavior both positively and negatively. These results allow improved modeling of FM-MCF based SDM systems, by including the impact of fiber splices, and thus more accurately estimating system capacity.

Acknowledgements

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