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Impulse Response Measurement of Spooled and Twisted Few-Mode Multi-Core Fiber for Short-Range Optical Links

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Abstract—The impact of bending and twisting on the impulse response matrix is investigated using optical vector network analysis. The heterogeneous 36-core 3-mode fiber under test is spooled at bending radii of 8 cm to 50 cm and additionally up to 4 twists per meter along the longitudinal direction are applied. The by-design large differential mode group delay of the fiber enables comprehensive measurement of the inter-mode-group cross-talk of the fiber impulse response matrix, which is directly measured with an optical vector network analyzer. A maximal inter-mode-group cross-talk of -28.1 dB is observed over all 36 cores. Furthermore, no significant changes related to the bending radii or additional strain by twisting the fiber were detected. These results demonstrate that the transmission characteristics of few-mode fibers with large differential mode group delay are fairly unaffected by bend- and twist-related perturbations which may prove beneficial for short-range mode-group multiplexed transmission systems using partial multiple-input multiple-output equalization in conjunction with mode-selective multiplexers.

Index Terms—Optical vector network analysis, space division multiplexing, fiber characterization.

I. INTRODUCTION

SPACE division multiplexing (SDM) is a widely-recognized technology in optical communications to increase the transmission capacity beyond the limits of conventional single-mode fiber (SMF). One way to categorize space-division multiplexing (SDM) transmission systems is to evaluate the amount of cross-talk between the spatial channels. Transmission systems with a high degree of cross-talk, using coupled spatial channels within a few-mode or multi-mode fiber,

typically employ a multiple-input multiple-output (MIMO) equalizer in the digital domain to invert the mode mixing. The computational complexity of the digital signal processing (DSP) algorithm scales quadratically with the number of spatial channels and linearly with the temporal length of impairments, making cost-efficient real-time implementations challenging. Alternatively, signals transmitted in fibers with low spatial channel cross-talk can be recovered by conventional low-order MIMO equalization for each mode-group, similarly to currently deployed coherent transmission systems [1]. A variety of experiments, using multi-core fiber (MCF) with low inter-core cross-talk between single-mode cores and without increasing the MIMO dimensions have been reported [2]–[4]. Moreover, a larger spatial multiplicity, and thus capacity, can be realized with few-mode multi-core fibers [5]. Mode coupling within mode-groups is stronger than the coupling between mode-groups, and both are significantly stronger compared to core-to-core coupling. Consequently, a $2N \times 2N$ MIMO equalizer is required to unravel the mixing between N modes in a single core. For fiber designs with small inter-mode-group cross-talk, the single MIMO equalizer can be replaced by multiple smaller sub-equalizers, one for each mode-group. These sub-equalizers can be operated in parallel to compensate for intra-mode-group cross-talk [6], [7]. In addition to low cross-talk fibers, spatial multiplexers with high mode selectivity are required.

In this work, we investigate the influence of fiber bending and twisting on the inter-mode-group cross-talk for 3 different waveguide designs in a heterogeneous 36-core 3-mode fiber using an optical vector network analyzer (OVNA). The inter-mode cross-talk is observed in the time domain impulse response as a plateau between the peaks originating from the strong mixing points within the multiplexers [8]. The visibility of this plateau improves when differential mode group delay (DMGD) is present in the device under test, resulting in a larger separation of mode mixing peaks. The large DMGD of the selected FM-MCF ensures that this plateau is also visible for shorter lengths. Additionally, the large diameter of the fiber allows investigation of the impulse response of the cores in the radial direction, which is influenced by an increasing stretching/condensing of the cores towards the cladding. However, the large diameter limits the bending radius in this work. Other mechanical issues related to the large diameter should be taken into account in any practical application [9]. The impulse

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Fig. 1: OVNA configured for analysis of the heterogeneous 36-core 3-mode fiber and 3D-waveguides (3DWGs). The fusion splicer (FS) and end-facet view of the glass processing system (GPS) are employed for core alignment.

response matrix of SDM components can be directly measured with a high temporal resolution using an OVNA [10]–[14]. No significant changes in inter-mode group cross-talk were observed for bending various fiber lengths with different radii or applying twists along the longitudinal direction to these spooled fibers. In combination with highly mode selective spatial multiplexers, the dimensionality of the MIMO equalizer can be reduced to multiple, smaller sub-equalizers for each mode-group, making FM-MCF with large DMGD a suitable candidate for short-reach optical interconnects where fiber bending is unavoidable.

II. OVNA SETUP FOR THE CHARACTERIZATION OF THE 36-CORE 3-MODE FIBER

The OVNA, based on swept-wavelength interferometry, is a measurement technique for obtaining the transfer function matrix and impulse response matrix of optical components, fibers, and subsystems with high temporal and spectral resolution over a large bandwidth in a single measurement with high dynamic range. Fig. 1 shows a spatially-diverse OVNA capable of measuring multiple spatial channels simultaneously by introducing fiber delays for each input and output port of the device in addition to the delay in the polarization multiplexing stage. The different interferometer lengths experienced by each spatial channel result in different frequency components in the interferogram detected by the polarization-diverse detector. Subsequently, these elements can be processed in the digital domain to reconstruct the $2N \times 2N$ impulse response matrix and with an inverse fast Fourier transform (IFFT) the transfer function matrix is obtained. From these matrices, any linear device parameter such as insertion loss (IL), mode dependent loss (MDL), or DMGD, can be extracted [12], [13].

The device under test (DUT) was a heterogeneous 36-core 3-mode fiber coupled to glass inscribed 3D-waveguide (3DWG) spatial multiplexers. The arrangement, labeling and refractive index profile of the 3 different core types are depicted in Fig. 2a. The refractive index difference of each core type to the outer cladding was 0.74%, 0.64% and 0.54%, for core types A, B, and C respectively. The effective index difference of the two mode groups were in the range between 3.8×10^{-3} and 3.9×10^{-3} . The relative refractive index difference to the corresponding trench was kept at 0.94% throughout all three designs [3]. As a result, the inter-core cross-talk was suppressed and higher-order modes other than the supported LP_{01} , LP_{11a} , and LP_{11b} are effectively cut-off. The cores were positioned on a hexagonal grid, with a pitch of $34 \mu\text{m}$ resulting

Scenario	Fiber length [m]	Bending radius [cm]	Number of twists
A	18	50	0
B	18	12.5	0
C	195	15	0
D	195	8	0
E	17.4	8	50
F	17.4	8	0

TABLE I: Evaluated scenarios in this work

in an outer diameter of $306 \mu\text{m}$. The large DMGD values ranging from 6.3 ps/m to 7.4 ps/m for all three core types resulted in a clear separation of the two LP mode groups. The attenuation ranged from 0.242 dB km^{-1} to 0.308 dB km^{-1} and the effective areas were $74 \mu\text{m}^2$ to $76 \mu\text{m}^2$ for the LP_{01} and $102 \mu\text{m}^2$ to $110 \mu\text{m}^2$ for the LP_{11} mode.

The employed single-core 3-mode multiplexers were aligned to the fiber core of interest using the fiber positioning and rotation mechanisms of a Fujikura ARCMaster FSM-100P fusion splicer and Vytran GPX-3000 glass processing system. The end-facet view of the latter device in combination with a visible light source was used for the alignment of the spatial multiplexer. The fine alignment was performed by optimizing the power transfer of a broad laser source, generated by the swept tunable laser (SWL) with coherence control enabled to increase the laser linewidth to 40 MHz. The alignment was further improved by observing the spectrum of the captured interferogram and maximizing the frequency components corresponding to the transmitted signal, while simultaneously minimizing any frequency components related to reflections between the 3DWG and the FM-MCF.

The OVNA was configured with the following delays: 0.4 m for τ_p , 3.2 m, and 6.4 m on the inputs, and fiber delays of 1, and 2 m at the outputs of the DUT. With these delays, a maximum impulse response duration of 1.9 ns, or approximately 265 m of the FM-MCF could be measured. The SMF delay τ_r was matched to the length of the DUT to maintain a low frequency interference pattern and minimum analog-to-digital converter (ADC) sample rate for reduced computation times. Back-to-back measurements were performed to calibrate the system.

In the digital domain, the received interferogram of the DUT and the reference arm was sampled to a linear frequency sweep using the interference pattern detected from an auxiliary interferometer. After an IFFT of the re-timed dual-polarization data channels, digital windows were placed at the positions corresponding to the laser sweep rate of 100 nm/s and the interferometer path length differences τ_p , τ_{in} , and τ_{out} , resulting in the impulse response and transfer function matrices. The

Fig. 2: (a) Core labeling of the FM-MCF and refractive index profiles of the 3 different core types. (b) Summed impulse responses of cores 1-1, 2-2, 3-3, 4-4, 5-4, 6-4, and 7-4 for scenarios C and D. Scenario A and B for the center-core (4-4) are depicted in the shaded area.

configuration employed in this work had a maximum dynamic range of 48 dB with an optical frequency sampling interval of 1.4 MHz, which translates to a sampling interval in the order of 200 fs in the temporal domain.

III. IMPACT OF FIBER BENDING ON IMPULSE RESPONSE

The impact of bending radius on the impulse response of few-mode fiber cores is investigated by comparing a 50 cm bending radius (scenario A), which represents an un-spooled fiber, with a typical fiber spool radius of 12.5 cm (scenario B). The average of the measured 6 $\times$ 6 impulse response matrix of the center core (4-4) is depicted in the shaded area of Fig. 2b. Observe that the impulse response and derived DMGD of 148 ps are similar in both scenarios, hence the impact of spooling on the impulse response of this 18 m fiber is limited. The smaller peaks originate from reflections due to the build-in shutters of the polarization controllers. Note that these peaks are relatively small, appear outside the main impulse response of interests, and their position is known.

In the next comparison of scenarios C and D, the bending radius is reduced and the fiber length is increased to 195 m. The first is expected to increase any mode coupling by the increased strain of bending the fiber. By increasing the fiber length, and thus also the accumulated DMGD, the distance between two main peaks in the impulse response is increased. Consequently, a larger and flatter plateau section is to be expected in the impulse response measurements. The large diameter fiber easily broke when spooled at small bending radii. To prevent any defects during the manual re-spooling, fiber drums with radius 8.15 cm were selected. Note that the same 195 m section of FM-MCF was spooled on both drums to exclude any effects related to localized manufacturing imperfections of the fiber or end-facet cleaves. For scenarios C and D, the transfer function matrices of the cores along the diagonal (1-1, 2-2, 3-3, 4-4, 5-4, 6-4, and 7-4) were obtained sequentially by aligning the spatial multiplexers to the core of interest. The sum of the 36 impulse response elements for the measured 7 cores at both bending radii are shown in Fig. 2b. For all 7 cores, 2 very similar distinct impulse response peaks corresponding to the 2 mode groups can be seen. The obtained mode dispersion for the cores in ascending order of the core

number is 1.47 ns, 1.22 ns, 1.37 ns, 1.45 ns, 1.20 ns, 1.32 ns and 1.27 ns. Dividing these values by the expected DMGD for each fiber core type results in an expected length of the DUT of 195 m, which holds nicely for core 1-1 to 5-4, but the estimates for core 6-4 and 7-4 are slightly lower. From the distance between the peak and level of the plateau in these impulse responses, the cross-talk between the mode groups at a bending radius of 15 cm (scenario C) ranges from -28.6 dB to -30.9 dB. For the 8 cm bending radius of scenario D, the cross-talk ranges from -28.1 dB to -30.6 dB. These values should have a minimum impact on transmission performance, enabling partial MIMO transmission over 3 modes [1].

IV. IMPACT OF FIBER TWISTING ON IMPULSE RESPONSE

As a result of the induced strain on the fiber by twisting the fiber along its longitudinal axis, the mode mixing and inter-mode group coupling may increase. To determine the maximum strain that can be applied to this large-diameter fiber, several short lengths of FM-MCF were twisted to determine the breaking point, which was around 4 twists per meter for this particular fiber. To minimize the probability of breaking the fiber during the manual twisting and spooling steps, a comparable length to scenarios A and B was chosen. Taking the likely breaking point into account, 50 twists were applied to a 15 m section of FM-MCF. The twists were held in place with fiber clamps with approximately 1 m of untwisted fiber at both sides to reach the alignment stages. This fiber was then spooled on the smallest fiber reel of 8 cm radius which is labeled scenario E. After obtaining the impulse response matrix of all 36 fiber cores, the fiber was un-spooled, the twists were removed, and the fiber was re-spooled on the same reel for the measurements of scenario F. The average of the 6 $\times$ 6 impulse response matrix of each core in both scenarios are depicted in Fig. 3. The colors of the core numbers match the colors in the layout and index profiles of Fig. 2a. Within each core, no noticeable difference in the impulse response was observed by applying additional strain to the fiber. An average cross-talk of -32.7 dB, with a maximum of -29.4 dB for core 2-5 and a minimum of -35.6 dB for core 4-4 is observed for the twisted fiber. These values are similar to the untwisted fiber of scenario F for which an average crosstalk of -32.7 dB

Fig. 3: (a) Averaged impulse response matrix for each core of the FM-MCF with (scenario E) and without twists (scenario F).

was observed, with a minimum of -35.9 dB for core 5-4, and a maximum of -29.1 dB for core 1-2.

From each impulse response, the DMGD was estimated by determining the spacing between the two major peaks. Fig. 4 shows these estimated values after division by the fiber length of 17.4 m. Note that any differences between the twisted and untwisted fiber are minimal. The estimated DMGD for cores of type A and B match closely with their designed values. Core type C shows a slightly larger DMGD, which matches with earlier observations during transmission [3]. For the cores on rows 6 and 7, a lower dispersion is measured, which coincides with the measurements for cores 6-4 and 7-4 in the previous section. Since these lower DMGD values for these cores are observed in multiple measurements with different spooled fiber sections, the influence of bending seems unlikely.

V. CONCLUSION

The impact of strain induced by fiber bending and twisting in a heterogeneous 36-core 3-mode fiber with large DMGD has been experimentally investigated. The measurements show no significant changes in the impulse response and mode group cross-talk when the bending radius changes in the range 50 cm to 8 cm. Furthermore, adding 50 twists along the longitudinal

direction to 15 m FM-MCF spooled at an 8 cm radius also had no significant impact on the impulse response and cross-talk. With measured cross-talk levels below -28.1 dB, this by-design large DMGD FM-MCF in combination with mode-selective spatial multiplexers may be suitable for 3-mode partial MIMO transmission over short distances where fiber bending and twisting is unavoidable.

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Fig. 4: Differential mode group delays derived from the impulse response measurements of spooled fiber with (scenario E) and without (scenario F) twisting compared to the designed values of the three core designs.