Distributed Supermode Coupling Measurements in Multi-Core Optical Fibers

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Abstract: Coupling of supermodes in multicore fibers is investigated exploiting an OFDR to measure each core when injecting light into another one. Distributed analysis of cross-core coupling is reported for the first time in multicore fibers. © 2020 The Author(s)

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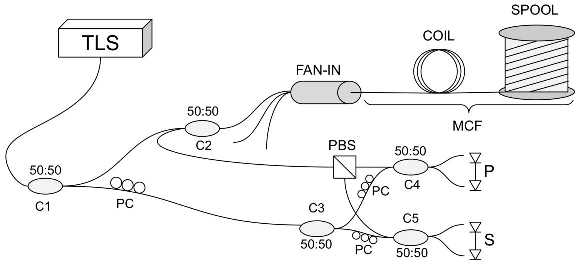
1. Introduction

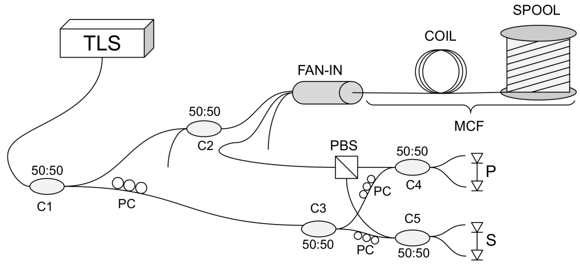
Recently, multi-core fibers (MCF) have been gaining increasingly high attention in the perspective of spatial division multiplexing [1], in which each of the supermodes supported by the fiber should be exploited as an independent communication channel. In this work we perform a distributed analysis of cross-core coupling effects along the fiber by the analysis of the Rayleigh scattering trace obtained from each fiber's core when the probing signal is launched in a specific one. The measured fiber is an array ring 3-core MCF, equipped with a proper fan-in device. The scattering traces are measured by means of coherent frequency-domain reflectometry [2].

2. Experimental setup

The fiber has been characterized in two configurations, shown in figures 1a and 1b. In both the experimental setups, light coming from a tunable laser source is split in the two arms of a Mach-Zender interferometer, one of them being connected through coupler C2 to one port of the fan-in (i.e to one core). In the figure 1a case, the other C2's port is connected to a polarization beam splitter (PBS). The signal coming from the local oscillator is mixed with the MCF's backscattering after the PBS, at C4 and C5, providing balanced coherent detection for the two orthogonal polarization components. In this way, two same-core (SC) traces are acquired, one for each polarization. The second setup is shown in figure 1b. In this case, the PBS is directly connected to a different port of the fan-in, in order to obtain two cross-core (CC) traces for each the other two cores. The C2 coupler has been left in order to maintain the launching condition in the MCF as stable as possible. Both setups are equipped with an auxiliary Mach-Zender interferometer used to compensate nonlinearities in the frequency swept [3]. After the fan-in, about one meter of straightened MCF fiber is followed by an about 6.5-meters-long span that is gently coiled on a flat surface with a radius of 15 centimeters, avoiding twists as much as possible. Then the fiber enters a spool around which is rolled-up with uncontrolled twist and strain. The bandwidth of the measurements is $\Delta f \simeq 8.3$ THz, leading to a spatial resolution of $\delta z \simeq c_0/(2\,\Delta f\, n_g) = 12.2$ µm, using $n_g = 1.466$ as reference refractive index. The length of the analyzed fiber section is 20 m.



(a)



(b)

Fig. 1: Experimental setup. Figure (a): setup for the same-core measurement. Figure (b): setup for the cross-core measurement. TLS: tunable laser source; PC: polarization controller.

3. Polarized backscattered power

The analysis of the power backscattered on the two orthogonal polarization components reveals some useful information. The measured SC and CC traces are shown in figure 2. Data have been smoothed by a 4-mm-long moving average filter to improve the visibility of polarization effects over Rayleigh fading noise. The backscattered field amplitude is reported on the y axis for both polarizations, as a function of the distance. The leftmost graph in fig. 2 refers to the SC trace, recorded from the same core where the light was injected. We notice that the trace characteristics in the first 12.6 m are markedly different from the rest of the trace. This corresponds to the fact that in the first meters the fiber is gently coiled on a flat surface. This particular fiber disposition, characterized by the absence of strong twists, reflects in the presence of few deterministic coupling effects among the cores. In this situation, most of the injected power remains on the lighted core, leading to an higher backscattered level.

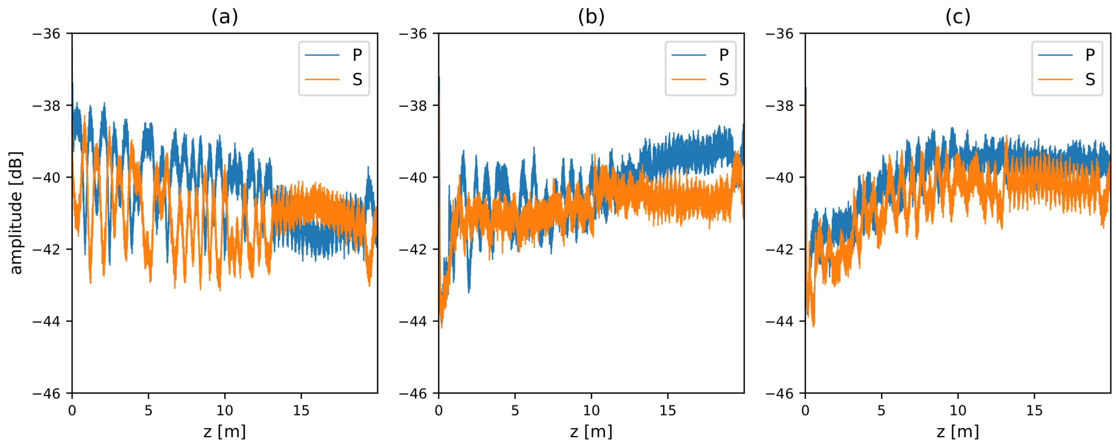


Fig. 2: Rayleigh scattering traces. Figure (a): same-core. Figure (b): cross-core 1. Figure (c): cross-core 2.

This situation completely changes after 12.6 m, where fiber is already spooled. The random twists experienced by the fiber when rolled-up, set it in a strongly-coupled regime, in which the light, on average, tends to spread on all the three cores [1]. Similar considerations can de drawn through the inspection of the figure 2 (b) and 2 (c). Again, clearly visible oscillations characterize their first sections. In the CC case, however, the backscattered amplitude tends to increase along the distance because of the increasing coupling efficiency among supermodes. As was for the SC measurements, in the spooled fiber section the coupling is patently different. Incidentally, it can be noted that all the backscattering signals asymptotically approach the same amplitude, corresponding to a 4.8 dB decrease for the SC, i.e 1/3 split, and an equivalent increase for the CC.

4. Spectral correlation analysis on the Rayleigh traces

Other information can be extracted from the Rayleigh scattering thanks to the so-called spectral correlation analysis (SCA) [4], different from the previously proposed time-domain correlation analysis [2,5] . The technique exploits the fact that the Rayleigh scattering is a fully-fledged fingerprint of the fiber span generating it: as long as the fiber is in stable conditions, its backscattering signal is invariant. Due to the noise-like shape of the Rayleigh scattering, the similarity between two measurements of the same fingerprint has to be found by means of correlation. Although slight perturbations acting on the fiber, e.g small termperature changes, can lead to hardly-recognizable time (space) domain Rayleigh traces generated by the same fiber, they have not such a strong effect in the frequency domain: this is the reason why correlation is performed between the respective spectra. It's worth saying that, due to the random nature of the Rayleigh scattering, two fingerprints show spectral similarity only if generated by the same fiber span. Let's now contextualize this analysis to the the cross-core measurements considered in this work. Each supermode generates its peculiar Rayleigh scattering, consisting in a specific linear combination of the fingerprints of the cores. Since different supermodes share the same cores, the respective signatures will show spectral similarity. This fact can be exploited to perform a distributed SCA between SC and CC measurements. To this aim, a reference window is placed on the SC trace, identifying a specific fiber span, and the related spectrum computed. At the same time, a second window (called the "analysis" window), is placed on the CC trace, initially aligned with reference one. Tracking the magnitude of the spectral cross-correlation peak between the reference and analysis spectra, as a function of position of the reference window (i.e position within the fiber) and relative shift between the two windows, allows to estimate the relative delays among supermodes, leading to the plot reported in figure 3. In particular, figure 3 refers to the measurement pair (SC, CC2), but analogous information can be derived from the (SC, CC1) pair too. Position of the reference window and relative delay are respectively reported on x and y axis. The color scale represents the correlation magnitude. An interpretation of this plot is that, for a certain position z along the fiber, the y position in which the maximum occurs equals the windows' relative delay such that they contain the signature of the same fiber span. According to previous arguments, this represents the cumulated delay up to z between two supermodes whose signatures show spectral similarity. It's known that mechanical perturbations acting on MCFs can locally change the DGD between specific couples of supermodes, leading to high delays cumulated in short fiber spans. From that point of the fiber on, that couple of supermodes will show the locally cumulated delay, as happens, e.g at position 2.1 m, where a replica of the supermode's fingerprint appears with a delay of about 1.5 ps. Clearly, this occurs in the first 12.6 m. Then, according to previous arguments, the fiber enters in a strongly-coupled regime, leading to a continuous

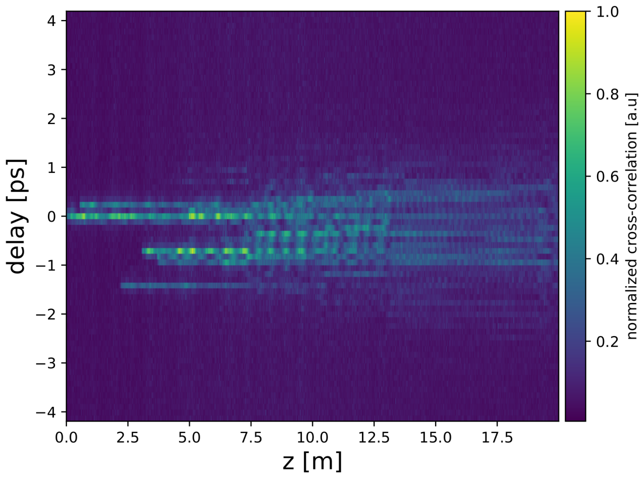


Fig. 3: Spectral correlation analysis performed on same-core and cross-core 1 measurements.

exchange of power between supermodes. Each exchange of power actually generates a replica of a supermode which in turn gives rise to a specific signature. This traduces in several low-power overlapped signatures coming at many different delays, leading to the correlation traces that can be seen from $z = 12.6$ m on.

5. Conclusions

In this work we have shown two ways to characterize coupling among supermodes of an MCF, based on the analysis of the Rayleigh traces. While the direct inspection of the scattered signals gives a rapid overview of the coupling occurring among supermodes, the SCA provides a much more detailed analysis, able to identify specific coupling events. While promising, these preliminary results require further investigations to fully exploit the richness of details.

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