# Exploiting Rayleigh Signature Invariancy for Centimeter-Resolved Mode Dispersion Measurement in Few-Mode Fibers

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***Abstract*** *A new scheme for spatially resolved measurement of mode dispersion in few-mode fibers is presented and experimentally validated on a 4-mode-group fiber. The analysis relies on spectral correlation analysis between fiber's coherent Rayleigh backscattering traces generated by each of the supported mode groups.*

## Introduction

Few-mode fibers (FMF) are widely known as a space division multiplexing capable transmission medium. In this scenario, each of the supported modes is exploited as an independent transmission channel and the modal dispersion (MD) becomes one of the critical fiber properties to take into account when designing the receiver. The set of available techniques for the measurement of the fiber's cumulative modal dispersion is well stocked[1],[2]; however, distributed measurements, providing local information, are also possible. Recently, the spectral correlation analysis (SCA) technique has been proposed to this aim[3]; it's based on proper analysis performed on the fiber's coherent Rayleigh backscattering signal.

In it's very first demonstration, the SCA has been successfully exploited to measure MD between the $LP_{01}$ and $LP_{11}$ mode groups (MG) simultaneously propagating in a two-mode-group FMF. However, the proposed scheme is not suitable for the full characterization of fibers supporting an higher number of MGs. In this work, we propose a novel scheme to overcome such limitation, and we validate it performing a complete distributed characterization of MD and modal birefringence (MB) - i.e. the difference in effective refractive index, in a 4-mode-group step-index FMF.

## Limitations of the previous scheme

Firstly proposed SCA scheme[3] relies on two properties of the Rayleigh backscattering, namely uniqueness and spectral shift properties. The first one states that the Rayleigh spectral signature of a specific fiber span is unique or, in other words, that the signatures of two different fiber spans are completely uncorrelated. The second one states that the Rayleigh signature of a fiber span depends on the propagation constant of the fiber's mode that generates it; more precisely, non-degenerate modes produce spectrally-shifted Rayleigh signatures (in first order approximation). Furthermore, the shift is proportional to the difference between the modes' propagation constants, i.e. to MB. According to this, the SCA works by cross-correlating the spectra of different sections of the fiber's Rayleigh trace in order to reveal a correlation peak. Owing to the uniqueness property, the peak appears as soon as the two sections contain the signature of the same fiber span, i.e. they are *spatially* aligned for a specific mode-group pair. In this case, the relative delay between the sections shows the cumulated MD, while the position $\Delta f$ of the peak shows the MB through $\Delta n \simeq n_0 \Delta f / f_0$[3], where $n_0 = 1.466$ is a reference refractive index and $f_0$ the carrier frequency.

Under proper power constraints, the optical fiber behaves as a linear medium. Owing to this property, the electric field forward-propagating in a multi-mode fiber can be expressed as a linear combination of the supported modes' fields. Clearly, the same applies for the Rayleigh signal generated by the propagation of such mode mixture. In particular, it corresponds to a linear combination of the Rayleigh signatures independently generated by each mode.

Assume now to perform a coherent Rayleigh scattering measurement $b(t)$ in a fiber in which

N non-degenerate MGs are simultaneously propagating. Furthermore, assume to select two sections of equal length $T$, namely $\mathcal{S}_1(t), t \in [t_1, t_1+T]$ and $\mathcal{S}_2(t), t \in [t_2, t_2+T]$, of the backscattering measure $b(t)$. Owing to previous considerations and to the non-degeneracy of the N MGs, the spectrum of $\mathcal{S}_1$ will correspond to the superposition of the signatures of N different fiber spans $Z_{1,n} = [t_1 v_{g,n}/2, (t_1+T)v_{g,n}/2], n \in \{1, \ldots, N\}$, where $v_{g,n}$ is the group velocity of the $n$-th MG and the factor 2 accounts for round-trip propagation. Same applies for the spectrum of $\mathcal{S}_2$, with $Z_{2,n} = [t_2 v_{g,n}/2, (t_2+T)v_{g,n}/2], n \in \{1, \ldots, N\}$.

Assume now to perform SCA between $\mathcal{S}_1$ and $\mathcal{S}_2$. Due to the linearity of the cross-correlation, the spectral correlation of the two sections traduces in a summation of N$^2$ terms. Even assuming the *spatial* alignment between $\mathcal{S}_1$ and $\mathcal{S}_2$ for a specific MG pair $(i, j)$, i.e. $Z_{1,i} \equiv Z_{2,j}$, the resulting summation would contain one informative term versus N$^2$-1 noise terms, coming from uncorrelated signatures generated in different fiber spans. This leads to a measurement SNR $\propto$ 1/N$^2$, rapidly scaling down as the number of propagating mode-groups increases. In the next section we will show how to overcome this problem.

### The new scheme

It comes straightforwardly from the previous analysis that the key point is to limit the number of simultaneously propagating MGs during the backscattering measurement. However, the presence of different modes' signatures in the correlated sections is obviously a mandatory requirement for the SCA to be effective. In order to allow the characterization of several MGs while maintaining the SNR as high as possible, another Rayleigh backscattering property comes into help: the invariancy property. It states that, as long as the fiber is not perturbed, the Rayeligh signature generated in a fiber span is invariant in time[4]. This suggests that the sections $\mathcal{S}_1$ and $\mathcal{S}_2$ subject to spectral cross-correlation can be selected on different backscattering measurements; even then, whenever spatially aligned for a MG pair, the spectral correlation of the two sections will reveal a correlation peak. In the case only mode $i$ is propagating during measurement $b_1(t)$ and mode $j$ during measurement $b_2(t)$, the highest SNR in characterizing mode pair $(i, j)$ is achieved. We recall that the only requirement is for the fiber to remain unperturbed between the two correlated measurements.

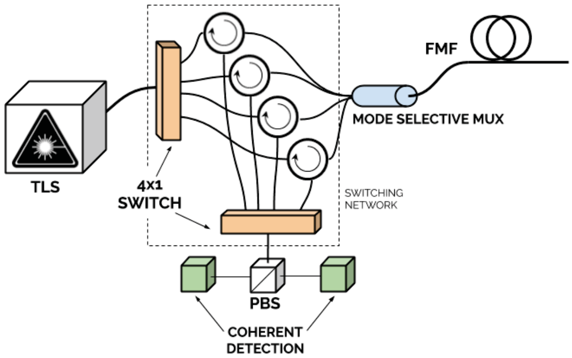


**Fig. 1:** Experimental setup. TLS: tunable laser source, PBS: polarization beam splitter, MUX: multiplexer.

### Experimental setup

All the above conditions can be satisfied with the setup shown in figure 1. An optical frequency-domain reflectometer (OFDR) setup is exploited to obtain coherent high-resolution polarization-diverse measurement of the Rayleigh scattering. The switching network, together with the mode selective multiplexer (e.g. a photonic lantern), allow the selection of the launched MG without perturbing the fiber. The fiber's signature generated by each MG can therefore be collected by consecutive measurements while the fiber remains in a stable state. Subsequently, the SCA can be performed between different measurements, revealing MD and MB for the selected mode pair. Whenever this scheme is implemented, the only limit resides in the *spatial* similarity of the correlated MGs. Indeed, the spectral shift property holds only in first approximation when dealing with signatures of non-degenerate modes; in reality, a signature depends also on the spatial distribution of the generating mode. As a consequence, modes having very different field distributions can lead to faint spectral correlation peaks.

### Results

The proposed scheme has been validated on a 4-mode-group step-index FMF[5], equipped with a mode-selective photonic lantern[6]. The TLS sweep bandwidth $\mathcal{B}$ was set to roughly 8.5 THz, resulting in a sampling step $dt \simeq 0.13$ ps or equivalently $dz \simeq 12$ µm; $dt$ directly determines the resolution in the MD measurement; $dz$ determines the spatial resolution through the window length, which was set to 2048 samples $\simeq$ 2.5 cm. The window length also affects the resolution $\delta n$ in the MB measure through the sweep bandwidth $\mathcal{B}$, being approximately equal to $\delta n \simeq 3.1 \cdot 10^{-5}$. The measurements of the modes' signatures have been carried out consecutively and as fast as possible, in order to rule out any effect brought by environmental fluctuations. The polarization-diversity scheme at receiver allows to measure the signature for two orthogonal states of polarization; for each mode pair, the SCA has been performed over all the 4 possible combinations of the two polarization states. Such analysis returns a volumetric dataset $C(p, t, \Delta t, \Delta f)$, representing the cross-correlation value at $\Delta f$ when section $\mathcal{S}_1$ starts at $t$ and section $\mathcal{S}_2$ starts at $t + \Delta t$, for the combination of polarization states identified by $p$[3]. Initially, the maximum of $C$ with respect to $p$ has been computed; this step is needed to rule out polarization effects and leads to the 3-dimensional dataset $C'(t, \Delta t, \Delta f)$. The information regarding MD has been extracted taking the maximum of $C'$ with respect to the $\Delta f$-axis. On the other hand, the MB was revealed taking the maximum of $C$ with respect to the $\Delta t$-axis. In order to perform a complete characterization of MD and MB, it's sufficient to measure their values for each MG with respect to a fixed reference one. According to that, we measured MD and MB with respect to the fundamental $LP_{01}$ MG.

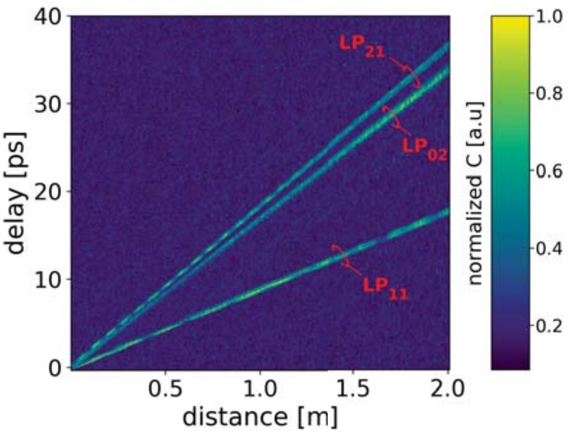


**Fig. 2:** Experimental results for the MD with respect to the $LP_{01}$ mode group.

Figure 2 shows the results obtained for the MD. $\Delta t$ is reported on the y-axis while $t$ (properly scaled to a position along the fiber through $n_0$) is reported on the x-axis. Each SCA analysis returns a 2D image showing only one tilted trace, representing the evolution of the group delay (GD) between a particular mode pair. However, for the sake of compactness, all the images have been merged in one taking the pointwise maximum. Before that, each image was normalized to its own maximum. The obtained plot clearly shows the cumulation of GD between $LP_{01}$ and all the other MGs during propagation; the slopes of the tilted traces correspond to two times the differential group delay (DGD) between the corresponding mode pair (the factor of two accounts for round-trip propagation). The obtained results are summarized in table 1 and show a very good agreement with the nominal values[5].

**Tab. 1:** Measured DGD versus $LP_{01}$ in ps/m

| $LP_{11}$ | $LP_{02}$ | $LP_{21}$ |
|---|---|---|
| 4.4 | 8.4 | 9.1 |

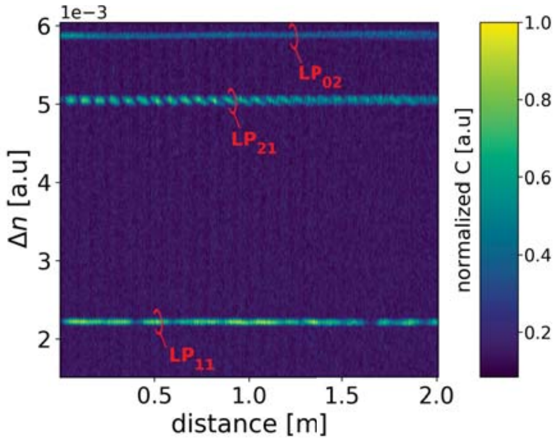


**Fig. 3:** Experimental results for the MB with respect to the $LP_{01}$ mode group.

Figure 3 shows the results obtained for the MB. $\Delta n$ is reported on the y-axis, while position along the fiber is reported on the x-axis. Interestingly, the $LP_{02}$ MG shows a higher MB than $LP_{21}$, despite having a smaller DGD. A summary of the obtained results is reported in table 2. In both plots, the oscillating amplitude of the correlation peak is related to mode coupling phenomena; it's exploitment in a quantitative evaluation is the subject of on-going studies.

**Tab. 2:** Measured $\Delta n$ versus $LP_{01}$

| $LP_{11}$ | $LP_{02}$ | $LP_{21}$ |
|---|---|---|
| 2.21 $10^{-3}$ | 5.85 $10^{-3}$ | 5.02 $10^{-3}$ |

## Conclusions

In this work we have shown how to perform a spatially-resolved complete measure of the mode dispersion in FMFs supporting several mode groups. The analysis provides values in very good agreement with the nominal ones with centimeter spatial resolution and sub-picosecond delay resolution.


## Acknowledgements

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