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Experimental characterization of mode content in fibers using S^2 imaging without a DFT

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ABSTRACT

Spatially and spectrally resolved imaging, the so-called S^2 imaging technique, is a method to determine the modal content of multimode fibers, the power carried by each mode, and the Multi-Path Interference (MPI) level. However, a drawback of this approach is the need for a highly stable and precisely tunable laser source, since Discrete Fourier Transformation (DFT) is used to extract time delays and reconstruct the powers of mode beatings. This work demonstrates both theoretically and experimentally that a “DFT-free S^2 method” can identify and quantify the modal content of a fiber probed under different conditions by simple spatial correlation analysis of images recorded at different wavelengths.

1. INTRODUCTION

The accurate knowledge of the modal content of non-purely Single-Mode Fibers (SMF) is a common problem in different fields of photonics. In telecom, it has been demonstrated that Few-Mode Fibers (FMFs), supporting N spatial modes, have the capability to surpass the capacity limits of SMF imposed by the non-linear Shannon limit and offer an factor N of capacity increase [1]. However, the cross-talk induced by mode coupling in FMF reduces the transmission reach and/or limits the transmission bandwidth [2]. In the field of high-power fiber lasers, Large Mode Area (LMA) fibers are developed to increase the threshold of appearance of nonlinear effects, but such fibers are rarely purely single-mode, which leads to the degradation of the spatial quality of the beam [3]. Therefore, methods that can permit an accurate analysis of the individual properties of the guided modes in a MMF are highly suited. From this observation, this work will present a measurement technique and data processing method that is capable of determining (i) the modal content of FMF, (ii) the power carried by each mode, and (iii) the MPI level.

The analysis technique presented here is based on the use of data obtained with the well-known spatially and spectrally resolved imaging (S^2) technique. In its standard implementation which we will refer to as the “DFT-based S^2 method” the measurement setup consist of a highly stable, wavelength-tunable laser which is injected into the fiber under test (FUT), and a camera which records the intensity image of the FUT end face [4]. The generated dataset consists of a stack of intensity images at evenly spaced laser wavelengths. From this dataset mode beating and MPI levels can be extracted. A drawback of the DFT-based S^2 method is the need for a highly stable and precisely tunable laser source since the data treatment is based on a DFT of the dataset along the wavelength direction and Fourier domain filtering. Indeed, if the laser presents jitter in wavelength as it is scanned, peaks in the Fourier domain can be completely washed out rendering this technique completely inaccurate to extract the modal content [5].

In the present work, it is proved experimentally that, using the same dataset but without performing a DFT, the modal content can be identified. This method which we will refer to as the “DFT-free S^2 method” was previously introduced by us [5] but only theoretical demonstrations were presented. The experimental validation presented in the following through the study of a 4-mode (LP₀₁, LP₁₁, LP₂₁, and LP₀₂) step-index fiber and two cases, namely low and high MPI regimes.

2. MODAL CHARACTERIZATION OF AN OPTICAL FIBER

2.1 Theoretical approach

Assuming linearly polarized fields, the electric field associated to the guided mode k of a fiber can be expressed as follows [5]:

$$E_k(x, y, \omega) = \sqrt{P_k} F_k(x, y) e^{i\omega t} e^{-i\beta_k z} \quad (1)$$

where $\sqrt{P_k}$ represents the amplitude of the electric field, F_k the transverse field profile, $\omega = 2\pi c/\lambda$ the angular frequency and β_k the propagation constant of the mode. So, if we suppose that the fiber supports N guided modes, the near-field intensity I recorded after a fiber length L can be written in a simplified form after removing the constant part (mean value over λ) as:

$$\tilde{I} = \sum_{i=1}^M \Pi_i B_i \hat{e}_i \quad (2)$$

M will stand for the total number of beatings ($M = N(N-1)/2$), $\Pi_i = 2\sqrt{P_k P_l}$ beating power, $B_i(x, y) = F_k(x, y)F_l(x, y)$ is the product of the transverse fields, and \hat{e}_i is equal to $\cos(\omega\tau_i - \phi_i)$ where τ_i is the group delay between different modes and ϕ_i a constant phase shift.

The DFT-free S^2 method described in this work is based on analyzing the spatial correlations within the dataset. In order to do this, the intensity profiles recorded for each λ_j are assembled into a matrix denoted X of dimension $P \times N$ (P is the number of pixels and N is the total number of images), each column of this matrix is going to be an image captured at wavelength λ_j where the intensity constant part (mean value over λ) is removed to obtain \tilde{I} .

The variance-covariance matrix C is calculated by the following equation:

$$C = N^{-1} X X^T \quad (3)$$

Using relation (2) and noting that scalar product $\langle \hat{e}_i | \hat{e}_j \rangle = \frac{1}{\Delta\omega} \int \hat{e}_i \hat{e}_j d\omega = \delta_{ij}$ if the spectral range of analysis is sufficient, the correlation matrix C can still be written as [5]:

$$C = B \hat{P} B^T = V D V^T \quad (4)$$

\hat{P} is a diagonal matrix whose elements are equal to $0.5 \Pi_i^2$ and C is a real symmetrical matrix, which means that it can be diagonalized (matrix D) and its eigenvectors $|V_i\rangle$ are orthogonal to each other. Each eigenvector corresponds to a principal component (PC) of matrix X .

2.2 Link between Principal Components and Beatings

We use herein the results of the theoretical development published in ref. [5] and invite the reader interested to read sections IV and after. In this paper, the results suggest that if the power carried by the HOMs is low compared to that of the fundamental mode (low MPI regime), beatings and their corresponding powers can be extracted by diagonalization of the matrix X . Moreover, the PCs are equivalent to the beating patterns and the eigenvalues will allow to extract the power in the beatings. However, this statement is no longer true if the power carried by HOM is not negligible (high MPI regime typically when MPI is higher than -15 dB) and, in this case, a general formula is given to reconstruct the powers.

Thus, it was theoretically demonstrated in Ref. 5 that it is possible to identify the modal content and their power distribution from the same dataset as used in DFT-based S^2 by a different treatment, DFT-free S^2 , through spatial correlation analysis. Such an approach can be very useful when operating in wavelength ranges where stable tunable lasers do not exist (mid-IR for example). In this case, the standard technique based on an analysis in the Fourier domain will fail to extract the modal content of the fiber because peaks of HOM will be completely washed out.

In the present work, the experimental demonstration of some theoretical statements developed in reference [5] is made through the example of a 4-mode step-index fiber.

2.3 Results: Analysis of beatings in the presence of wavelength jitter

In this analysis, a fiber length equal to 36 m was used. Its refractive index profile is plotted in Fig.1 together with the effective indices calculated at the wavelength of 1267 nm. This fiber guides 4 spatial modes, namely LP_{01} , LP_{11} , LP_{21} and LP_{02} at this wavelength.

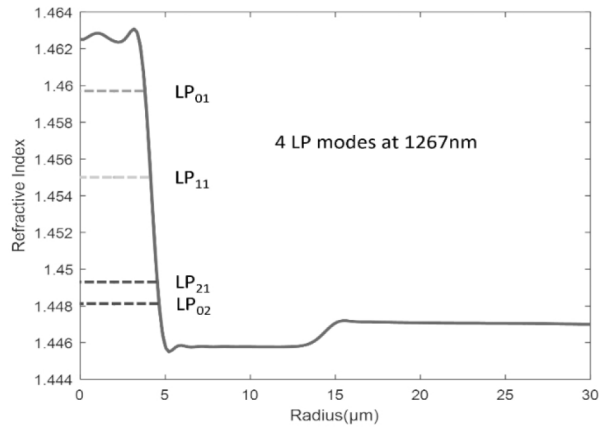


Figure 1: In blue: refractive index profile of the fiber under test (FUT). Dashed horizontal segments: effective indices of the core-guided modes at 1267 nm.

To check the resistance of the present method to the jitter of the laser line, two cases were studied, namely low and high MPI regimes. In each case two measurements are performed. For the first measurement (Method 1), a constant wavelength step size is used. To do so, a tunable laser whose wavelength was regularly incremented by 4 pm between 1267 and 1269 nm was used to record the data. A feedback control loop including a wavemeter was implemented to guarantee wavelength accuracy below 1 pm. For the second measurement (Method 2), a jitter of the laser line was emulated by randomly shifting the wavelength after each step. In practice, wavelength was once again regularly incremented by 4 pm but a random shift of 300 pm maximum amplitude was applied after each step.

Low MPI regime:

The FUT was excited by an SMF in a centered injection configuration so as to ensure that the fundamental mode is preferentially excited, making the power carried by the HOMs small.

The experimental Fourier spectra extracted from the DFT-based S^2 method are shown in Fig. 2(a). The red curve shows three peaks and is obtained with Method 1 for which only the natural laser jitter (± 1 pm) can alter the data. In this case, beating figures are extracted from a filtering in the Fourier domain following ref. [6]. The band-pass filter corresponds to grey boxes in Fig. 2(a). Reconstructed beatings are shown on the top row in Fig. 2(b).

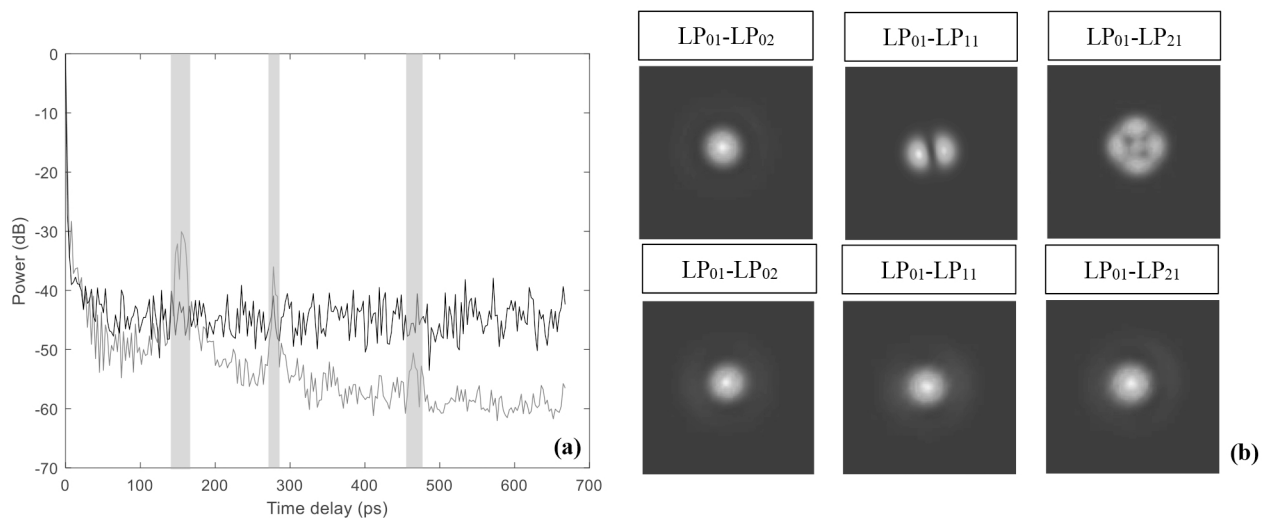


Figure 2: (a) Fourier spectrum obtained for a low wavelength jitter (red) and a 300 pm amplitude random jitter (black), (b) Beating figures are extracted using a filter in the Fourier domain (grey boxes). Beatings are presented in the order of the peaks, from left to right. **Top:** natural laser jitter (± 1 pm). **Bottom:** random jitter of 300 pm

The black curve corresponds to the situation where a random jitter of 300 pm is applied (Method 2). As expected, when the laser jitter is large, no peak can be detected in the Fourier spectrum: in this case, figures extracted from a filtering in the Fourier domain do not correspond to easily identifiable beating of modes as can be seen in Fig. 2(b) bottom row. The standard method does not make it possible, in this case, quantifying the number of guided modes and thus the real level of MPI since the black curve exhibit a mean constant level around -44 dB whatever the time delay, as compared to the red curve.

On the contrary, Fig. 3 shows the first three PCs resulting from the processing of the same data set using the DFT-free S^2 method. It can be noticed that even in presence of a large jitter, beatings are perfectly reconstructed resolving, in this case, the problem presented by the standard method.

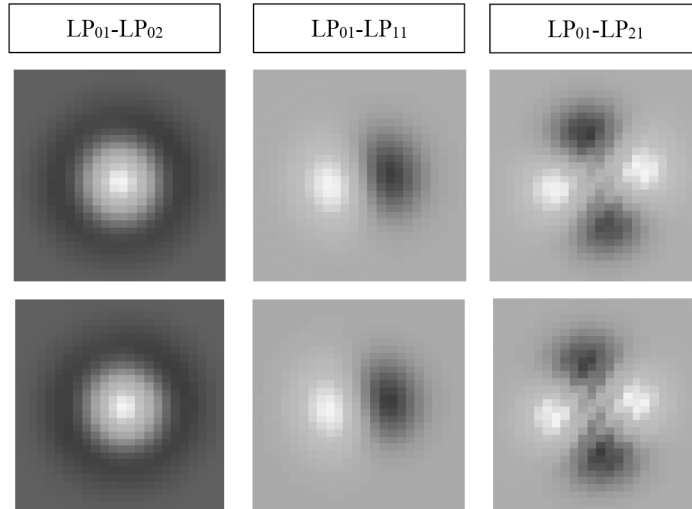


Figure 3: PCs deduced from PCA-based analysis. **Top:** Method 1: 4 pm wavelength step without random jitter. **Bottom:** Method 2: 4 pm wavelength step with 300 pm random jitter.

Table 1: Normalized eigenvalues of \mathbf{C} obtained with DFT-free S^2 method

Jitter (in pm)	Eigenvalue for LP ₀₁ -LP ₀₂	Eigenvalue for LP ₀₁ -LP ₁₁	Eigenvalue for LP ₀₁ -LP ₂₁
± 1	1.000	0.248	0.004
300	0.992	0.257	0.004

At low MPI, it has been demonstrated that eigenvalues of PCs are proportional to the product of power $\Pi_i^2 = 4 P_k P_l$ carried by modes k and l . We expect then that eigenvalues are not sensitive to jitter. In Table 1 are reported the three normalized eigenvalues corresponding to the three beatings LP₀₁-LP₀₂, LP₀₁-LP₁₁, and LP₀₁-LP₂₁ for the two cases. The normalization is done on the highest eigenvalue, in this case on LP₀₁-LP₀₂.

As can be seen, the eigenvalues are very similar for a laser jitter of ± 1 pm and for a random jitter of 300 pm, which is remarkable knowing that the random jitter is about 75 times the wavelength step. The maximum error is around 3.5% on the beating LP₀₁-LP₁₁.

High MPI regime:

The same FUT was then excited by the same SMF in an off-centered condition. In practice, a lateral offset of 2.5 μm was adopted between the cores so as to favor the excitation the HOMs. By calculating the overlap integral between the LP₀₁ mode of the SMF and the modes of the FUT – considering a lateral offset of 2.5 μm between the cores – it is verified that a high MPI regime (> -15 dB, typically) is effectively reached. The offset value was controlled with a piezoelectrical positioner combined to an home-made code that automatically determines the centered injection configuration and hence precisely control the offset value that can be applied.

Similarly, to the low-MPI case, the experimental Fourier spectra extracted from the standard method are shown in Fig. 4(a). The red curve (Method 1) shows six peaks, the three extra peaks, compared to Fig. 2, being attributed to the beatings between HOMs. In this example, only the major beatings (i.e. beating between the fundamental mode and the HOMs) are represented.

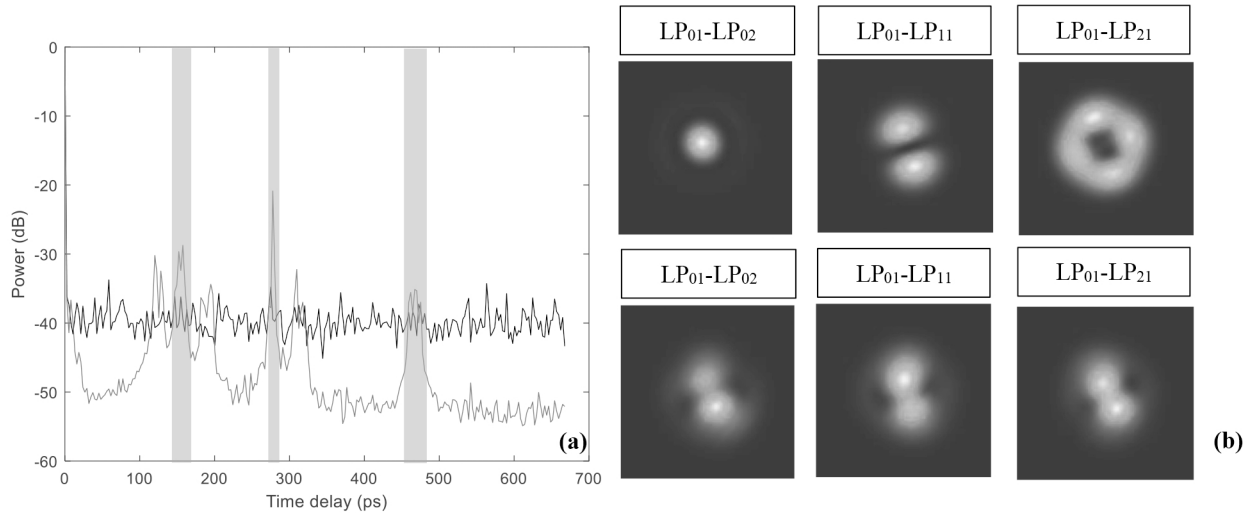


Figure 4: (a) Fourier spectrum obtained for a low wavelength jitter (red) and a 300 pm jitter (black). (b) Beating figures extracted using a filter in the Fourier domain (grey boxes). Beatings are presented in the order of the peaks, from left to right. **Top:** natural laser jitter (± 1 pm). **Bottom:** random jitter of 300 pm

Again, no peak is observed on the black curve (Method 2), due to the high jitter value.

As previously, beatings patterns (Fig. 4b) are correctly reconstructed in the case of low jitter (top row) but no valuable information can be obtained from the black curve in high jitter regime, showing that the standard processing of S^2 data fail to extract correct mode beatings in high jitter regime,

On the contrary the DFT-free treatment of this dataset, presented in Fig. 5, shows its ability to find the modal content in high jitter regime (bottom row vs top row).

As previously, the normalized eigenvalues are reported in Table 2.

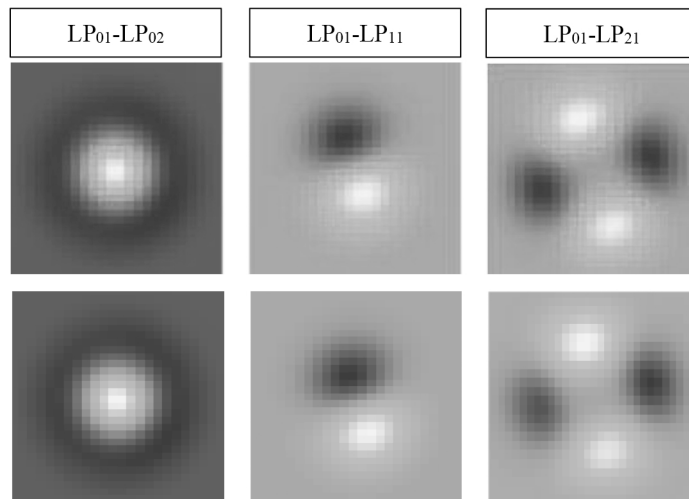


Figure 5: PCs obtained for (a) low jitter and (b) high jitter of 300 pm. **Top:** Natural laser jitter. **Bottom:** 300 pm laser random jitter

Table 2: Normalized eigenvalues of **C** obtained with DFT-free S² method

Jitter (in pm)	Eigenvalue for LP₀₁-LP₀₂	Eigenvalue for LP₀₁-LP₁₁	Eigenvalue for LP₀₁-LP₂₁
± 1	0.536	0.993	0.090
300	0.524	1.000	0.088

Values in Tab. 2 show once again that the eigenvalues of the three PCs represented in Fig 5 are conserved for a laser jitter of ± 1 pm and for a random jitter of 300 pm. Only an error of 2.4% is observed between Method 1 and 2 on the beating LP₀₁-LP₀₂. The method hence appears robust to wavelength jitter even with non-negligible MPI. In this example, we notice that the eigenvalue for LP₀₁-LP₁₁ is larger than the others; this is explained by the fact that at 2.5 μ m lateral offset between cores, LP₁₁ is more excited than the other HOMs. This is not the case in a centered injection configuration where LP₀₂ is the dominant HOM (see Table 1).

3. CONCLUSION

It has been shown experimentally that the modal contents and the power distribution between modes of an FMF excited under different conditions can be identified by simple spatial correlation analysis between images recorded at different wavelengths. This correlation-based method can be applied in situations where the standard DFT-based approach does not work, such as when the tunable laser used for S² imaging has significant jitter. This affirmation is true for low and high MPI regimes in the fiber under test.

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REFERENCES

- [1] D.J.Richardson, J.M.Fini and L E.Nelson, "Space Division Multiplexing in Optical Fibers, "Nat. Photon. 7, 354-362 (2013).
- [2] Joseph M. Kahn; Keang-Po Ho, "Mode coupling effects in mode-division-multiplexed systems, " IEEE Photonics Society Summer, paper TuC3.4 (2012).
- [3] C. Jauregui, T. Eidam, J. Limpert, and A. Tunnermann, "Impact of modal interference on the beam quality of high-power fiber amplifiers, " Optics Express, vol. 19, no. 4, pp. 3258–3271, February (2011).
- [4] Duc Minh Nguyen, & al, "Modal decomposition technique for multimode fibers, " Applied Optics, February (2012)
- [5] Yves Quiquempois, & al, "Mode recovery by S² imaging without a Fourier Transform," Journal of lightwave technologies, Vol.39, Issue 13, pp. 4453-4461(2021)
- [6] Jeffrey W. Nicholson, & al, "Measuring the Modal Content of Large-Mode-Area Fibers, "IEEE journal of selected topics in quantum electronics, Vol.15, No.1, January/February (2009)