Distributed Polarization and Coupling Analysis of a 3-Coupled-Core Fiber

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Abstract: OFDR-based, distributed characterization of polarization and coupling properties of a 3-coupled-core fiber is reported. Results highlight the beating among the supermodes of the fiber, enabling the evaluation of their polarization and modal birefringence.

1. Introduction

Space-division multiplexing (SDM) is an interesting technique to sustain the capacity growth in optical transmission systems [1]. Among the different approaches to SDM, coupled multicore fibers (MCF) are attracting much interest due to several beneficial features they offer [2]. An accurate modelling of propagation along these fibers requires a detailed description of their local coupling properties, in terms of both polarization and modal birefringence between the supermodes. This description can be in principle achieved by Rayleigh-based distributed measurements [3, 4]. Nevertheless, the approach described in Ref. [4] analyzes only power coupling, whereas the method described in Ref. [3] is not effective for small birefringence values, as the one typically encountered in coupled MCFs.

In this work we describe an alternative data analysis approach, most befitted for low-birefringent MCFs, that enable the quantitative analysis of polarization and modal birefringence. The soundness of the proposed method is confirmed by preliminary experimental results obtained on a coupled-core 3-core fiber.

2. Theoretical model of distributed measurements

In the most general case, the field backscattered by a reciprocal MCF with N cores can be expressed as [5]

$$\hat{\mathbf{b}}(\omega) = \left\{ \int_0^L e^{-j2\beta_{\mathrm{av}}(\omega)z} \mathbf{F}^T(z,\omega)\mathbf{S}(z)\mathbf{F}(z,\omega)dz \right\} \hat{\mathbf{a}}(\omega)\,, \tag{1}$$

where $\hat{\mathbf{a}}(\omega)$ is the $2N$-dimensional vector with the spectra of the complex amplitudes of each input mode of the MCF, $\hat{\mathbf{b}}(\omega)$ are the corresponding backscattered spectra, β_{av} is the average scalar propagation constant common to all modes, $\mathbf{F}$ is the $2N \times 2N$ Jones matrix describing forward propagation, and $\mathbf{S}$ is and $2N \times 2N$ matrix describing Rayleigh scattering [5]. When (1) describes an OFDR, the input vector can be written in the time domain as $\mathbf{a}(t) = p(t)\mathbf{a}_0$, where $\mathbf{a}_0$ describes how the input light is distributed among the modes and $p(t)$ is an equivalent input pulse with length equal to the spatial resolution of the measurement. For OFDRs, this length is typically in the order of a few tens of micrometers. Moreover, under the assumption that dispersive phenomena are negligible, which holds for short fiber sections and small dispersion, the frequency-dependence of $\mathbf{F}$ can be neglected. Therefore, the inverse Fourier transform of (1) yields $\mathbf{b}(z) = \mathbf{F}^T(z)\boldsymbol{\sigma}(z)\mathbf{F}(z)\mathbf{a}_0$, where $z = v_{\mathrm{av}}t/2$, v_{av} is the average group velocity and $\boldsymbol{\sigma}(z) = \int_z^{z+\Delta} \exp(-j2\beta_{\mathrm{av},0}z')\mathbf{S}(z')dz'$ describes the random nature of the Rayleigh scattering, i.e. it represents the Rayleigh fingerprint of the fiber. The equation $\mathbf{b}(z) = \mathbf{F}^T(z)\boldsymbol{\sigma}(z)\mathbf{F}(z)\mathbf{a}_0$ describes the complex field measured along the fiber by an OFDR, when the above assumptions are valid.

So far, we have generically mentioned the "modes" of the fiber. Actually, when describing MCF that are two possible choices. The first one is considering the supermodes of the fiber [7]; the second one is to consider the MCF as mode of coupled single-mode cores. While the two descriptions are totally equivalent, we opt for the second approach for clarity. Actually, in this case, the Rayleigh fingerprint matrix $\boldsymbol{\sigma}(z)$ can be well approximated as the block-diagonal matrix $\boldsymbol{\sigma}(z) = \mathrm{diag}\left(\sigma_1(z)\mathbf{I}, \sigma_2(z)\mathbf{I}, \ldots, \sigma_N(z)\mathbf{I}\right)$, where $\mathbf{I}$ is the 2×2 identity matrix and $\sigma_k(z)$ is the Rayleigh fingerprint of the kth core. This expression is justified by the fact that, when a single core is illuminated, the light that is scattered directly into the other cores is largely negligible. In the light of this consideration, the field backscattered from the kth core, when only the hth one is illuminated reads

$$\mathbf{b}_k(z) = \sum_{n=1}^{N} \sigma_n(z)\mathbf{F}_{n,k}^T(z)\mathbf{F}_{n,h}(z)\mathbf{a}_{0,h}\,, \tag{2}$$

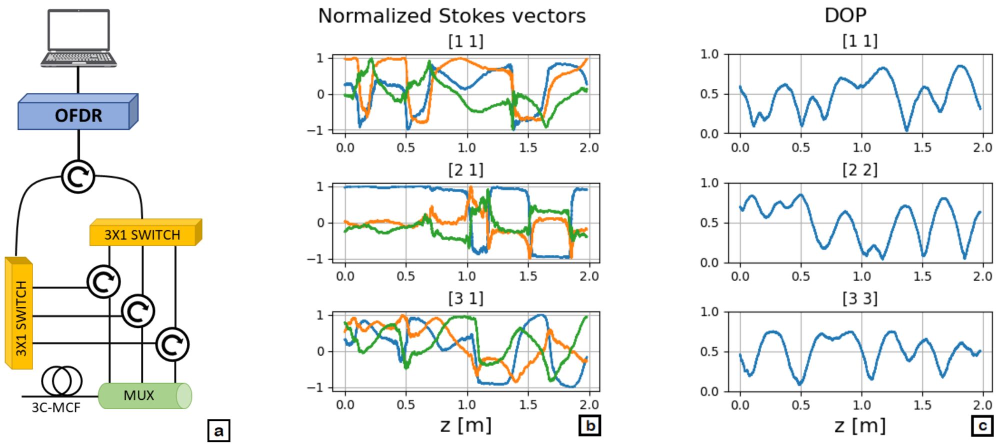

Fig. 1. a) Experimental setup. b) Normalized Stokes vectors and c) Degree of Polarization

where $\mathbf{F}_{n,h}$ is the 2×2 block of $\mathbf{F}$ in position (n,h). The above expression describes how each core of the fiber contributes to creating the light backscattered on the considered one.

Note that the quantity $\mathbf{b}_k(z)$ is apparently noise, because it still directly depends on the cores' fingerprints. To highlight the coupling effects, i.e. the z-dependence of the matrix $\mathbf{F}(z)$, we calculate the coherency matrix, $\mathbf{C}(z) = \langle \mathbf{b}_k(z)\mathbf{b}_k^*(z)\rangle_w$, where * is transpose conjugation, and $\langle\cdot\rangle_w$ represents the ergodic average over a distance window of length w. This distance is chosen to be longer with respect to the spatial scale of the fingerprints $\sigma_n(z)$, but shorter than that of $\mathbf{F}(z)$. This is indeed possible since the former is in order of the spatial resolution of the OFDR, i.e. few tens of micrometer, whereas the later is in the order of many millimeters and above. Exploiting the fact the the core fingerprints have zero average and are statistically independent of each other, and considering for simplicity the case in which light is launched and measured from the same core (i.e., $k = h$), we find

$$\mathbf{C}_k(z) = \langle \mathbf{b}_k(z)\mathbf{b}_k^*(z)\rangle_w = R\sum_{n=1}^{N}(\mathbf{F}_{n,k}^T\mathbf{F}_{n,k}\mathbf{a}_{0,k})(\mathbf{F}_{n,k}^T\mathbf{F}_{n,k}\mathbf{a}_{0,k})^* = R\sum_{n=1}^{N}\mathbf{C}_{k,n}(z)\,, \tag{3}$$

where $R = \langle|\sigma_n(z)|^2\rangle_w$ is the average backscattering coefficient, assumed equal for all cores, and $\mathbf{C}_{k,n}$ is the coherency matrix of the light associated to the fingerprint of the nth core and backscattered to the core k, when the probe light is launched only from core k. To clarify the meaning of this result, notice that the coherency matrix of a field is just a linear combination of the elements of the associated Stokes vector $\bar{S}$. Indeed, in general we have $\mathbf{C} = (1/2)\bar{\Lambda}\cdot\bar{S}$, where $\bar{\Lambda}$ is the vector of Pauli matrices [8]. In this perspective, we can conclude that (3) is equivalent to $\bar{S}_k(z) = R\sum_n \bar{S}_{k,n}(z)$, which states that the Stokes vector of the light backscattered on core k is the sum of the Stokes vectors of the contributions associated to each core fingerprint. We may therefore expect that the degree of polarization (DOP) of the measured light is not necessarily equal to 1, as in single-mode fibers [6]. Rather, we should expect the DOP of the backscattered light to vary along the fiber.

An alternative analysis of the backscattered light, consists in evaluating the coherency matrix associated to the total backscattered field, i.e. the quantity $\mathbf{C}(z) = \langle \mathbf{b}(z)\mathbf{b}^*(z)\rangle_w$, which is equivalent to analyzing the generalized Stokes vector associated to the $2N$-dimensional field $\mathbf{b}(z)$ [10]. Also in this case, the random features of the fingerprints are averaged out, revealing the spatial fluctuations associated to coupling occouring along the fiber between polarization and spatial modes. In the next section we apply these analysis methods to experimental data.

3. Experimental results

The analysis methods described above have been applied to a set of measurements performed on a 3-core fiber. The experimental setup is shown schematically in Figure 1(a). It consists of a polarization-sensitive optical frequency domain reflectometer (OFDR) with a switching network to enable consecutive measurements for different combinations of launch and return cores, without perturbing the fiber; more details can be found in Ref. [3]. The measured MCF has 3 cores equally spaced among each other of about $29\mu m$ [9].

In a first experiment, the light is launched and measured on the same core and the measured Stokes vector is analyzed. Figure 1(b) shows the normalized Stokes vectors and Figure 1(c) the corresponding DOPs. In the case of a single mode fiber (SMF) one would expect an almost unitary DOP [6], whereas in Figure 1(c) we see that it oscillates widely. As predicted by the theoretical analysis made in the previous section, the measured Stokes vectors can be written as $\bar{S}_k(z) = R(\bar{S}_{k,1}(z)+\bar{S}_{k,2}(z)+\bar{S}_{k,3}(z))$, where $\bar{S}_{k,n}$ is the Stokes vector of the light that backscatteres on to core k while propagating in core n. Clearly the vectors $\bar{S}_{k,n}$ describes different polarization variations, leading to a possible decrease of the DOP. Specifically, decomposing the Stokes vector as $\bar{S} = (s_0,\,\bar{s})^T$,

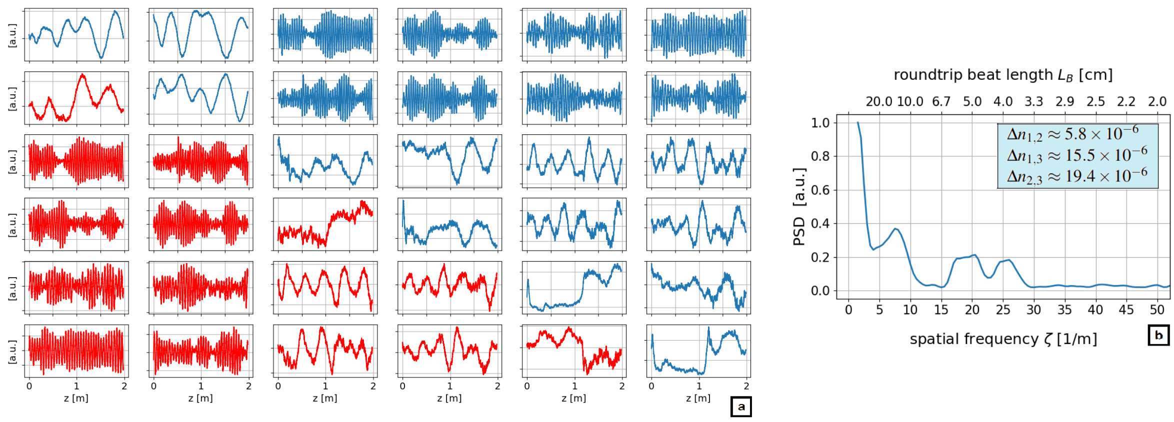

Fig. 2. a) Coherence matrix measured when light is launched in core 1. b) Average PSD derived from the coherence matrix with reported values of spatial mode birefringence

where s_0 is the intensity of the field, we can write the DOP measured on the k core as

$$DOP_k = \frac{|\bar{s}_k(z)|}{s_{k,0}} = \frac{|\bar{s}_{k,1} + \bar{s}_{k,2} + \bar{s}_{k,3}|}{s_{k,1,0} + s_{k,2,0} + s_{k,3,0}}; \quad (4)$$

whenever the three vector $\bar{s}_{k,n}$ sum up to almost cancel each other, the measured DOP drops to zero. Note that, when this happens, the measured SOP shows rapid local variations.

In a second experiment, the total backscattered field was measured when light is launched from one arbitrary core. Figure 2(a) shows as an example the coherency matrix calculated in the launch port is core 1; similar results are obtained in the other cases. Because the coherence matrix is Hermitian, the upper triangle of the table in Fig. 2(a) reports in blue the real part of the matrix elements, whereas the lower triangle reports in red the imaginary parts. The rich spatial features are indicative of the coupling occuring among the modes. In particular, an ideal 3-core MCF supports 3 supermodes, two of which degenerate. In a real fiber we may expect the degeneracy to be broken because of both fiber non-ideality and external perturbations such as bending and twist, leading to 3 beating spatial frequency among the supermodes. Actually, this is confirmed by the PSD of the elements of the coherency matrix reported in Fig. 2(b), which has been evaluated over 75-cm-long windows, averaging among all the possible coherency matrices. We can clearly distinguish three peaks: the one with the lowest spatial frequency is associated to the beating between the two quasi-degenerate mode, whereas the other two peaks correspond to the beating between the other supermode and each of the quasi-degenerate ones. The corresponding modal birefringence Δn are reported in the inset of Fig. 2(b).

In conclusion, we have proposed novel analysis methods to characterize the coupling effects that takes place along coupled multicore fibers. The proposed methods are well supported by preliminary experimental results.

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