A direct method for measuring modal coupling and attenuation coefficients of few-mode fibers

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Abstract *We attempt to quantify minute cross-talk differences between two similar few-mode fibers. Coupled power equations are combined into a power transfer matrix approach so as to isolate the mode coupling and mode attenuation coefficients of the fibers from the (de-)multiplexer contribution.*

Introduction

Notwithstanding the practicality of single-mode fibers, applications have, over the past 15 years, pushed fiber designs to their limits so that the move to alternative fibers such as few-mode fibers (FMFs) is considered with increasing attention. The performances of FMFs for data transport are not only governed by their modal content but also by the attenuation and coupling coefficients of the guided modes [1]. To some extent these properties can be modelled during the fiber-designing stage, but experimental characterizations often diverge from predictions. Moreover, the experimental characterization remains delicate, in particular when it comes to isolating the fiber properties from those of the modal multiplexers (MUX) and de-multiplexers (DEMUX) [2, 3]. In this study, we introduce a direct method combining coupled power equations and power transfer matrix measurements which we apply to determine the mode coupling and mode attenuation coefficients of two similar 6-LP mode FMFs with different refractive index profiles (RIPs).

Methods

According to coupled power theory (see ref. [4]), the “system” power transmission matrix $[P_{System}]$ of the concatenation of a MUX, an FMF and a DEMUX can be expressed in matrix form as follows:

$$[P_{System}] = [P_{DEMUX}] \times e^{([\gamma])z} \times [P_{MUX}] \qquad (1)$$

Where $[P_{MUX}]$, $e^{([\gamma])z}$ and $[P_{DEMUX}]$ represent the power transfer matrix of the MUX, the FMF and the DEMUX. "e" in Eq. 1 corresponds to the matrix exponential. $[\gamma]$ is the matrix of mode coupling and mode attenuation coefficients and is of the form:

$$[\gamma] = \begin{pmatrix} -\left(2\alpha_1 + \sum_{\upsilon=2}^{N} h_{\upsilon 1}\right) & h_{12} & . & h_{1N} \\ h_{21} & -\left(2\alpha_2 + \sum_{\upsilon=1,\upsilon\neq 2}^{N} h_{\upsilon 2}\right) & & \\ . & & . & \\ h_{N1} & & & -\left(2\alpha_N + \sum_{\upsilon=1,\upsilon\neq N}^{N} h_{\upsilon N}\right) \end{pmatrix} \qquad (2)$$

Where $h_{\mu\upsilon}$ represent the power coupling coefficients, N the number of guided fiber modes (μ and υ serving as mode labels) and $2\alpha_\mu$ represent the mode attenuation (1/km)).

To estimate $[\gamma]$, the matrix $[P_{System}]$ is measured for two different fiber lengths, z_{long} and z_{short}, in the same way as a cutback measurement.

Combining Eq. 1 obtained with $z = z_{long}$ and $z = z_{short}$ gives:

$$[\gamma] \approx \frac{1}{z_{long} - z_{short}} \times \log\left([P_{long}]\right) - \log\left([P_{short}]\right) \qquad (3)$$

In the measurement $z_{long} > 20$ km and $z_{short} \sim 2$ m. "log" in Eq. 3 corresponds to the matrix logarithm. It should be noted that Eq. 3 is approximate and is exact only when $[P_{long}]$ and $[P_{short}]$ commute and are both positive-definite. Otherwise, error on estimating $[\gamma]$ has to be quantified and it has been validated that it remains low (≤ 0.0001 dB/km), in our case. The aim of the experimental implementation was to compare two FMFs with different RIPs but same modal content.

Experimental setup

The experimental setup (see Fig. 1) consists of an ASE source filtered at 1550 nm with a 1 nm bandpass-filter, a MUX, a DEMUX, and two optical switches to automate the measurement. Particular attention was paid to the number and quality of the splices between FMFs. MUX and DEMUX are Multi-Plane Light Converters (MPLC) from Cailabs [5]. The powers at the output ports of the DEMUX were measured with a powermeter.

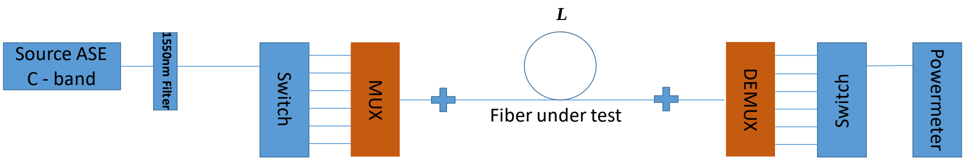

Fig. 1: Experimental setup of the system X-Talk matrix as a function of the fiber length.

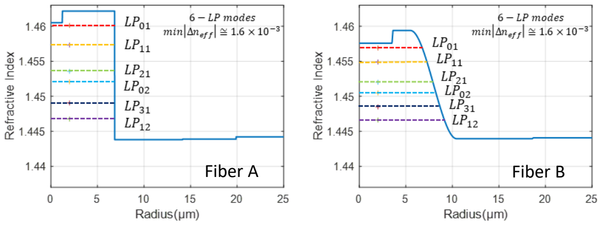

Fig. 2: Refractive index profiles at 1550 nm of 6-LP-mode fibers: Fiber A with a step-index core, Fiber B with a trapezoidal-index core. Effective indices of the guided modes are also reported.

Fibers under test

The two FMFs have inner depressed cores and the same minimum effective index difference between modes (1.6×10^{-3}) but different RIPs: step-index for Fiber A and trapezoidal index for Fiber B ([6, 7]) (see Fig. 2). The scattering-induced losses of these two fibers have recently been investigated [6].

Results

As known, the system X-talk (MUX-Fiber-DEMUX) can be deduced from $[P_{System}]$ by:

$$X_{\mu\nu} = 10 \times \log_{10}\left(\frac{P_{(mode_\mu)}}{P_{(mode_\nu)}}\right) dB \qquad (4)$$

$P_{(mode_\mu)}$ represents the power at the output of the fiber on the mode μ when the υ mode is excited. Tab. 1 represents the system X-talk matrix for a 25 km span of Fiber A. Based on Eq. 3, it is sufficient to measure $[P_{long}]$ and $[P_{short}]$ matrices in order to determine($[\gamma]$) i.e. the coupling and attenuation coefficients of a specific fiber, and accurately measure the fiber X-talk while eliminating any unwanted effects from MUX and DEMUX. Replacing $[P_{long}]$ in Eq. 3 by the power matrix measured for ~ 25 km and $[P_{short}]$ by the power matrix measured for ~ 2 m, the matrix $[\gamma]$ of the Fiber A can be extracted (see Tab. 2(a)). Knowing $[\gamma]$, the fiber power matrix can be deduced:

$$[P_{Fiber}] = e^{([\gamma])z} \qquad (5)$$

From this power matrix, the fiber X-talk matrix can be deduced for any length. Tab. 2(c) represents the fiber X-talk matrix for a 25 km long fiber span.

Tab.1: System X-talk matrix at 25 km long fiber (Fiber A).

X-talk (dB)	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
LP_{01}	0.00	-12.14	-21.22	-14.30	-22.63	-18.26
LP_{11}	-13.72	0.00	-12.87	-16.39	-20.17	-11.01
LP_{21}	-20.34	-10.81	0.00	-15.51	-12.41	-14.28
LP_{02}	-11.31	-12.08	-13.23	0.00	-16.63	-11.36
LP_{31}	-20.41	-15.78	-9.55	-16.94	0.00	-12.35
LP_{12}	-14.68	-6.22	-11.47	-11.91	-12.43	0.00

The comparison of Tab. 1 and Tab. 2(c) highlights that the X-talk matrix of the system at 25 km differs from the fiber X-talk matrix for the same length of fiber. As expected, the X-talk of the system is larger than that of the fiber. This discrepancy arises because the MUX and DEMUX generate X-talk. It is here demonstrated that the fiber X-talk matrix can be isolated using a direct method, even in presence of X-talk induced by MUX and DEMUX.

To determine the attenuation and coupling coefficients for a trapezoidal index fiber (Fiber B), the same procedure was applied using identical MUX and DEMUX. It should be noted that the $[\gamma]$ matrix is extracted for Fiber B for three different measurements cases: the first $[P_{long}]$ is measured for a fiber length of 20 km, the second for a fiber length of 40 km, and the third for a fiber length of 60 km.

Tab.2: a). Attenuation and coupling estimation [**γ**] in dB/km (Fiber A). Mode attenuations, α, at the bottom are deduced from summing each row of the matrix. **b).** Attenuation and coupling estimation [**γ**] in dB/km (Fiber B). **c).** Fiber X-talk matrix for 25 km -long fiber (Fiber A). **d).** Fiber X-talk matrix for 25 km -long fiber (Fiber B).

Fiber A

a)

γ (dB/km)	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
LP_{01}	-0.2612	0.0021	0.0005	0.001	0.0005	0.0008
LP_{11}	0.0023	-0.2954	0.0047	0.0033	0.0011	0.0019
LP_{21}	0.0006	0.0045	-0.3441	0.0028	0.0071	0.0042
LP_{02}	0.0009	0.0028	0.0026	-0.3653	0.0023	0.0066
LP_{31}	0.0005	0.0013	0.0084	0.003	-0.4009	0.0066
LP_{12}	0.0013	0.0024	0.0045	0.0077	0.0063	-0.4071
	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
α (dB/km)	-0.2557	-0.2823	-0.3234	-0.3475	-0.3836	-0.3871

c)

X-talk (dB)	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
LP_{01}	0.00	-19.22	-25.46	-22.38	-25.61	-23.55
LP_{11}	-18.72	0.00	-15.71	-17.18	-21.34	-19.38
LP_{21}	-24.11	-15.66	0.00	-17.55	-13.80	-15.91
LP_{02}	-22.62	-17.67	-17.93	0.00	-18.40	-14.19
LP_{31}	-25.19	-20.62	-13.15	-17.26	0.00	-14.14
LP_{12}	-20.86	-18.28	-15.61	-13.47	-14.27	0.00

Fiber B

b)

γ (dB/km)	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
LP_{01}	-0.2546	0.0018	0.0003	0.0001	0.0003	0.0006
LP_{11}	0.0015	-0.2503	0.0034	0.0022	0.0008	0.0004
LP_{21}	0.0003	0.0033	-0.2602	0.0029	0.0060	0.0023
LP_{02}	0.0005	0.0023	0.0028	-0.2924	0.0011	0.0048
LP_{31}	0.0003	0.0007	0.0057	0.0011	-0.2770	0.0008
LP_{12}	0.0006	0.0008	0.0032	0.0042	0.0008	-0.3065
	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
α (dB/km)	-0.2514	-0.2414	-0.2448	-0.2819	-0.2680	-0.2976

d)

X-talk (dB)	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
LP_{01}	0.00	-19.80	-27.25	-30.84	-28.45	-24.89
LP_{11}	-20.56	0.00	-17.11	-19.42	-23.38	-26.90
LP_{21}	-26.80	-16.98	0.00	-18.10	-14.84	-19.21
LP_{02}	-24.67	-18.14	-17.43	0.00	-21.63	-15.74
LP_{31}	-27.61	-23.42	-14.61	-22.09	0.00	-23.69
LP_{12}	-23.97	-22.48	-16.64	-15.95	-22.37	0.00

For the three mentioned cases, $[P_{short}]$ is considered the same and is measured for a fiber length of 2 m. As a result, $[\gamma]$ calculated using Eq. 3 for different lengths remains approximately equal, which proves the ability to find the mode attenuations and fiber mode coupling using fiber length ≥ 20 km (Tab. 2(b)).

Step-index fiber vs Trapezoidal index fiber

Tab. 2(a) and Tab. 2(b) present attenuation and coupling coefficient matrix for Fiber A and Fiber B using the same color scale. It should be noted that the attenuations extracted from the coupling matrix are very close to the measurements performed by OTDR. These tables show that most of the coupling coefficients (off-diagonal components) of Fiber A are larger than those of Fiber B. Mode attenuation and differential mode attenuation (DMA) are also larger for Fiber A. It can be deduced that even though Fiber A and Fiber B support the same number of LP modes and offer the same minimum effective index difference between modes, they present distinct $[\gamma]$ matrices and hence offer different performances for data transmissions. As has been presented in ref. [6], such a difference might be explained by the fact that Fiber A suffers from larger light scattering induced losses than Fiber B. To conclude the investigation on the performance of the two fibers, it was decided to compare the fiber X-talk matrices of both fibers for the same length. By comparing X-talk matrices of Fiber A (see Tab. 2(c)) and Fiber B (see Tab. 2(d)) at 25 km, it is evident that the X-talk of Fiber A is larger than that of Fiber B. Furthermore, the coupling matrices are quasi-symmetrical, whereas the XT matrices exhibit an asymmetry explained by differences in attenuation between the modes.

Conclusion

In this article, from a direct measurement of power and under certain assumptions, we can isolate the fiber X-talk matrix by determining the coupling coefficients and attenuation of each mode. As a result, the system X-talk appears larger than the fiber X-talk due to MUX and DEMUX effects. Thus, quantifying fiber performance requires determining the $[\gamma]$ matrix, as even fibers with the same number of LP modes and minimal effective index difference (Fiber A and Fiber B) may have different [γ] matrices and perform differently in data transfers. The observed differences are attributed to a different contribution of light scattering mechanisms.

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