Light Scattering Mechanisms in Few-Mode Fibers

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Abstract *The contributions of Rayleigh and small angle light scattering (SALS) mechanisms to attenuation for three different 6-LP-mode fibers are quantified and their impact on Differential Mode Attenuation (DMA) are analyzed. We show that a trapezoidal-index profile offers the best trade-off to reach low attenuation, low DMA and large effective-index differences between modes.*

Introduction

Space division multiplexing has been evaluated since 2010 to offer a capacity gain per fiber of up to a factor of one hundred compared to the best performance of Single-Mode Fibers (SMFs)[1]. In weakly-coupled Few Mode Fibers (FMFs), spatial modes can be used as independent data channels if the crosstalk induced by mode coupling is minimized. To this aim, these FMFs are designed to offer large effective index differences $|\Delta n_{eff}|$ between the different (groups of) modes. However, such FMFs can suffer from high attenuation and high Differential Modal Attenuation (DMA) that degrades transmission performance[2].

In 2019[5], we investigated the impact of Small-Angle Light Scattering (SALS)[3],[4] on DMA and demonstrated that the refractive index profile of the fiber plays a major role on this effect. In this paper, we quantify, for the first time to our knowledge, the contribution of both Rayleigh scattering and SALS for three different 6-LP-mode fibers. We show that SALS contribution and DMA in a trapezoidal-index profile fiber are equivalent to those of a graded-index profile, that presents the lowest SALS[4], while keeping the LP modes well isolated from each other.

Theoretical background

In the context of long-haul transmissions, the most desirable feature for an optical fiber is low attenuation. It is known that, for wavelengths close to 1.55 µm, the dominant contribution to optical losses is light scattering which is a combination of two factors:

- Rayleigh scattering which finds its origin in the physicochemical properties of glass and can be written as follows:

$$\alpha_R = \alpha_d + \alpha_c = \frac{A}{\lambda^4} \qquad (1)$$

where α_d corresponds to the density fluctuations frozen in the glass as it cools. Therefore, it depends on the fiber drawing conditions and, more generally, can be linked to the fictive temperature of the material[6]. The coefficient α_c corresponds to the fluctuations induced by glass doping necessary to constitute the core-cladding structure[7]. These two contributions induce losses proportional to $1/\lambda^4$ and the scattered intensity exhibits an angular dependence θ, relative to the fiber axis, described by the following equation:

$$I_R(\theta) \propto \alpha_R\left(1 + cos^2(\theta)\right) \qquad (2)$$

- SALS, also known in the literature as extra or anomalous loss, has been less investigated. A guided mode of an optical fiber is affected by the azimuthal and longitudinal fluctuations of the core-cladding interface which causes its coupling to radiation modes[4],[8]. SALS depends on the refractive index profile and, for example, it has been shown that, for an SMF, a larger contribution of SALS is expected for a step-index than for a graded-index profile that presents is known to minimize this effect[4]. In the space domain, SALS is concentrated within a

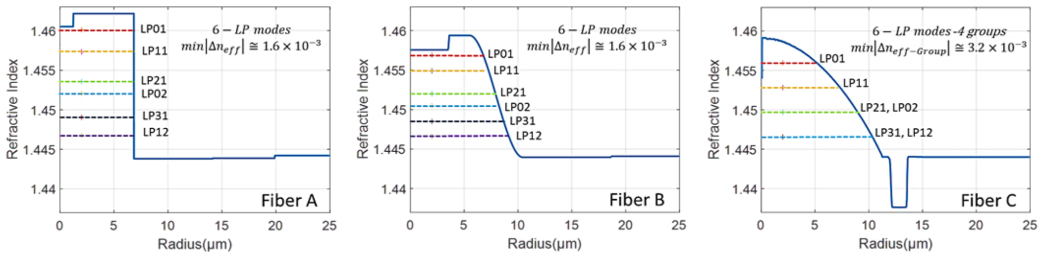

Figure 1: Refractive index profiles at 1550 nm of 6-LP-mode fibers: Fiber A with a step-index core, Fiber B with a trapezoidal-index core, and Fiber C with a graded-index core.

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small angular cone in the forward propagation direction. Hence, it has an angular dependence which is added to Rayleigh scattering for angles less than 50°, typically.

As they both depend on the spatial distribution of the refractive index and of core-cladding interface, these scattering mechanisms are mode dependent and it has been demonstrated that, in some cases, contribution of SALS increases with mode order[5]. However, their relative contributions have never been quantified, especially for the different modes of different types of FMFs. In this work, we will compare the Rayleigh scattering and SALS of three different FMFs that guide 6 LP modes and that have been designed to have large effective index differences between (groups of) modes to minimize the crosstalk.

Results and interpretation

The fibers that were analyzed in this work are presented in Figure 1:

- Fiber A[5] has a step-index profile with a depressed-index region in the core so that the minimum $|\Delta n_{eff}|$ ($min|\Delta n_{eff}|$) between modes is 1.6×10^{-3}.
- Fiber B[5] is a trapezoidal fiber with similar depressed-index region in the core and same $min|\Delta n_{eff}|$.
- Fiber C[9] has a graded-index profile with 6 LP modes divided into 4 groups with $min|\Delta n_{eff-Group}| = 3.2 \times 10^{-3}$. The modes within a group are strongly coupled with close-to-zero $|\Delta n_{eff}|$.

Table 1: Attenuation of the different LP modes of the three FMFs measured by OTDR.

Attenuation (dB/km)	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
Fiber A	0.26	0.28	0.34	0.31	0.36	0.37
Fiber B	0.24	0.24	0.26	0.24	0.26	0.26
Fiber C	0.21	0.21	0.21	0.21	0.25	0.25

Modal attenuations of the three FMFs were measured by Optical Time Domain Reflectometry (OTDR) combined with a mode multiplexer based on the Multi-Plane Light Conversion (MPLC)[10]. It was checked that crosstalk is low enough to have no impact on the measurements. The values are reported in Table 1. Attenuations vary from 0.21 to 0.37 dB/km for the different modes of the three FMFs. Fiber A suffers from a significant increase of attenuation as a function of the mode order (DMA~0.11 dB/km)[5], while this is not the case for the two others FMFs (DMAs of ~0.02 and ~0.04 dB/km for Fiber B and Fiber C, respectively). The quantification of Rayleigh and SALS contributions is thus needed to explain, on the one hand, the origin of the total losses and, on the other hand, the impact of the index profile. To quantify SALS and Rayleigh contributions, we used the experimental bench presented in Figure 2. A laser source emitting around 1.55 µm is successively modulated at low frequency, scrambled in polarization and injected into the input ports of a spatial multiplexer (MPLC). The output of the multiplexer is spliced to the FMF under test. Several meters after the junction, a stripped section of the fiber passes through a cylindrical tank filled with index matching liquid. Light scattered laterally from the fiber section in the center of the tank is imaged on an InGaAs detector whose output signal is connected to a lock-in amplifier that uses the low frequency modulation as a reference. Detector is installed on a motorized arm, which permits to collect the scattered intensity as a function of the angle while the optical power measured at the output end of the fiber is used for normalization.

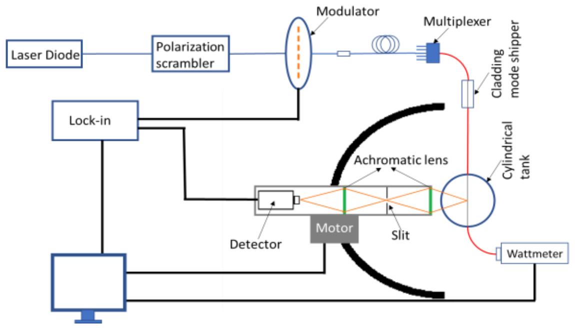

Figure 2: Experimental setup used to record the angular distribution of the scattered light in FMF.

We measured the angular distribution of the scattered light for the 6 LP modes, at 5 different positions of each FMF. Then, the experimental data were fitted using Eq.(2) for angles between 50° and 170° (an example is given in Figure 3(a)). Note that the intensity from 0° to 10° is assumed to be equal to that at 10°, due to the setup's limitation. It is observed that the curves obtained are well described by a Rayleigh law for the range of the fit. However, an excess of scattered intensity is observed in the domain of small angles, which is a clear signature of SALS. In Figure 3(b), the hatched section shows the difference between the total scattering $I_{T,exp}(\theta)$ and the Rayleigh curve $I_R(\theta)$ weighted by the solid angle $\left[I_{T,exp}(\theta) - I_R(\theta)\right] sin\theta$.

To extract the Rayleigh coefficient of a given mode, we use the integration of the Rayleigh curve over the solid angle on the 0-180° angular range for this mode and for the fundamental mode of an SMF of known Rayleigh coefficient used as a reference, $\alpha_{R,ref}$ (Eq. (3)).

$$\alpha_R = \frac{\int_0^{180} I_R(\theta) 2\pi\, sin\theta\, d\theta}{\int_0^{180} I_{R,ref}(\theta) 2\pi\, sin\theta\, d\theta} \times \alpha_{R,ref} \qquad (3)$$

To extract the SALS coefficient, we apply the following calculation:

$$\alpha_{SALS} = \frac{\int_0^{180} I_{T,exp}(\theta) 2\pi \sin\theta \, d\theta - \int_0^{180} I_R(\theta) 2\pi \sin\theta \, d\theta}{\int_0^{180} I_R(\theta) 2\pi \sin\theta \, d\theta} \times \alpha_R \quad (4)$$

Where α_R is the Rayleigh coefficient previously obtained.

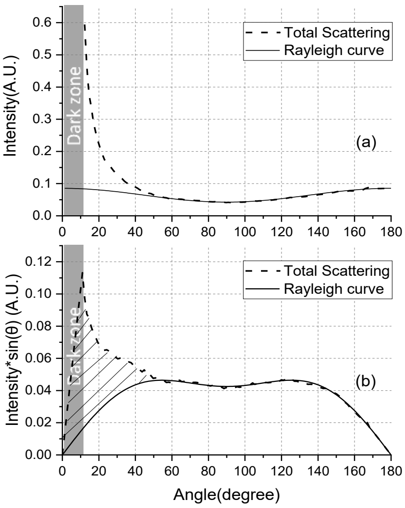

Figure 3: Example of a comparison between the theoretical Rayleigh curve (solid line) and the experimental total scattered intensity (dashed line). (a) the measured signal, (b) the measured signal weighted by the solid angle of scattering.

The Rayleigh and SALS coefficients of the different modes of each FMF are represented in Figure 4. Note that modes within a group in Fiber C have the same coefficients because they are strongly coupled. It can be noticed that the step-index (Fiber A) presents larger Rayleigh contribution than the two others FMFs, and that the graded-index (Fiber C) has the lowest one. This is mainly due to a higher core-cladding index difference[7]. Regarding SALS, it can be seen that it increases notably with the mode order for Fiber A due to the high index gradient at the core-cladding interface and contributes to about 0.07 dB/km to the total DMA of 0.11 dB/km[5]. The trapezoidal fiber (Fiber B) shows a very low SALS contribution of ~0.013 dB/km (DMA~0.02 dB/km) with small increase with the mode order, similar to what is observed for Fiber C. This latter graded-index profile presents the lowest SALS contribution <0.01 dB/km (DMA~0.04 dB/km), as predicted by theory for SMFs. This is confirmed here for the first time for FMFs. These results were compared to the total attenuations measured by OTDR. Figure 5 shows that these measurements are in good agreement with the sum of the scattering contributions (SALS+Rayleigh) derived from our analysis. The small differences are explained by the contributions of IR and UV absorptions (of the order of 0.01 dB/km)[11] and of OH absorption which mainly depends on the control of the environment during the preform manufacturing[12]. The difference between the total attenuation of the 4th mode group (LP_{31}-LP_{12}) in Fiber C and (SALS+Rayleigh) is explained by micro-bending effect[9].

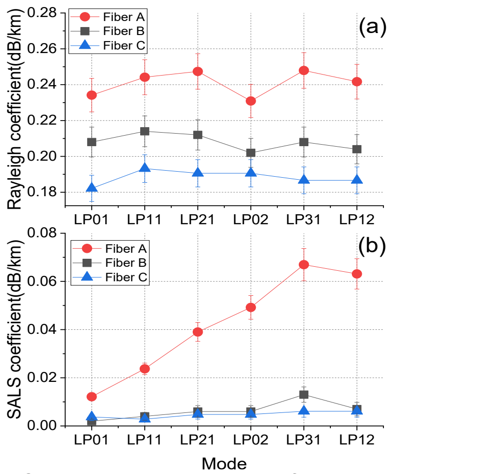

Figure 4: Contribution to the losses from light scattering mechanisms: (a) Rayleigh, (b)SALS

Conclusions

We quantified the Rayleigh scattering and SALS contributions in three FMFs presenting different refractive index profiles but the same number of modes. We showed that SALS contributes significantly to the total attenuation of the modes for the step-index profile whereas the trapezoidal-index profile exhibits a very low SALS, and thus a very low DMA, down to that of a graded-index profile, while keeping the LP modes weakly coupled. Such an index profile presents low crosstalk level (large $|\Delta n_{eff}|$) and low SALS, which is well adapted to weakly-coupled transmissions for which low attenuations and DMA are also critical.

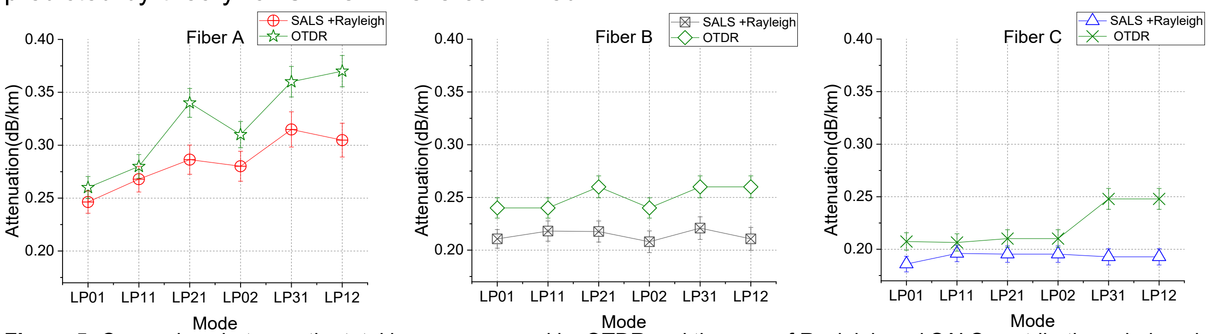

Figure 5: Comparison between the total losses measured by OTDR and the sum of Rayleigh and SALS contributions deduced from the light scattering measurements.

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