Experimental characterization of Plastic Optical Fibers for Under- and Over-Filled Injections

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***Abstract*—This study investigates the impact of under-filled and over-filled launching configurations on the transmission properties of Plastic Optical Fiber (POF). Experimental analyses on step and graded index fibers reveal differences in spatial and frequency properties under these launching conditions. Results show that the under-filled configuration leads to narrower radial profiles and Encircled Angular Flux (EAF) compared to the over-filled configuration. Additionally, under-filled launching produces better frequency response and larger bandwidth, particularly notable in shorter fibers. Results show that the under-filled launching significantly improves transmission properties, offering potential improvements in POF applications.**

Keywords— POF, Step index, Graded index, Launching conditions, Fiber characterization, Transmission properties, Frequency response, Bandwidth.

I. INTRODUCTION

In recent decades, the surge in popularity of optical fiber has been remarkable as the capacity to transmit vast amounts of data across great distances at high speeds was demonstrated in glass optical fibers (GOF). In fact, Single Mode Silica Fiber (SMF) is widely used for large scale communication networks. Nevertheless, SMF requires expensive active components that allow for precise alignment. Therefore, when short distances and moderate capacity requirements are involved. Plastic Optical Fibers (POF) are preferred as they exhibit several advantages [1]. The term POF is applied to a variety of fibres whose core and cladding are made of plastic materials, mainly poly(methyl methacrylate) (PMMA) and perfluorinated (PF) polymer. PF polymer fibres have core diameters similar to multi-mode GOFs (from 50 to 250 µm), while PMMA fibres have larger core diameters (normally 900 µm) and numerical apertures from 0.3 to 0.6. These later fibers are usually termed large-core POFs, and they have a very thin cladding, making their total diameter around 1 mm. Their large sizes and apertures allow them to transmit millions of modes, which results in a very high modal dispersion. Therefore, POFs exhibit higher attenuation and worse bandwidth than GOFs. However, their size and material allow them to be more flexible and rugged, while light coupling into them is far easier, which results in more cost-efficient installation and maintenance [2]. As a result, POFs are very useful in closed and small areas such as industrial and transportation applications (vehicles, aircrafts). Furthermore, POF can be utilized to create a smart home network.

There are two main types of POF, depending on the variation of their refractive index: Step-Index POF (SI-POF) and Graded-Index POF (GI_POF). The GI index profile offers a reduced modal dispersion and thus, GI-POFs are capable of transmitting higher data rates.

Among the different types of POF, this paper aims at exploring the transmission properties of PMMA 1-mm SI-POF and comparing them with those of a large-core PMMA GI-POF. In particular, this paper is focused on the experimental characterization of the transmission properties of POFs under different launching conditions. First, we present the experimental setups and devices used. In the next section, the experiments, measurement protocols, and data processing are described. Finally, section III includes the discussion of the results and the conclusions of the work providing an overview of POFs between under-filled and overfilled launching configurations analyzing their strength and emphasizing the differences in their capabilities.

II. EXPERIMENTAL SETUP

The experimental characterization has been focused in two configurations designed to achieve different launching conditions: under-filled launching conditions (UF) and over-filled launching conditions (OF). In the UF configuration, the light beam entering the fiber core is smaller than the fiber's core diameter and has a very narrow aperture (less than 1º) while the OF configuration occurs when the light beam entering the fiber core has a large aperture and is usually wider than the core diameter. With UF launching conditions, light is coupled only to the fiber lower order modes (angles), while in the OF light is coupled to all modes. The fiber launching conditions have a direct effect on the optical power coupled into the fiber and therefore it affects the optical power at the fiber output end and the effective length of the link.

The general experimental set-up is shown in Figure 1. This is how we will measure the output far field pattern (FFP), that describes the amount of optical power as a function of the propagation angle, and the S21 transmission parameter, that described the fiber frequency characteristics. These properties were measured for both UF and OF launching configurations. First, we will explain each piece starting from the laser going to the measuring device. The laser LP660 that has a pigtail of Visible Single-Mode fiber (V-SMF) connected to a variable attenuator to control de optical power. This pigtail is connected to a SMF with its appropriate connector, and this fiber is connected to the POF (directly, in the case of UF launching and through a 1-m POF segment with a scrambler, in the case of OF launching). The fibers used in the experiment were GH-4001 PMMA SI-POF (GH) from Mitsubishi and OM-Giga PMMA GI-POF from Optimedia (GI). The GH is a standard SI-POF with 0.5 numerical aperture while the GI is the only 1-mm PMMA GI-POF in the market. From the test fiber the FFP is registered using a system placed inside the sealed box set-up. To obtain the FFP, the output end of the fiber was placed at a distance of 7.5 cm from a white screen, and the reflected image was registered by means of a 12-bit monochrome camera (QICAM FAST 1394CCD) pointed to at an angle of 45º relative to the camera. This system is driven by a LabVIEW program, which reads the FFP images and calculates their radial profiles and Encircled Area Fluxes (EAFs). The set-up is inside of a sealed box to avoid any undesired light. In addition, the box has a small orifice for the optical fiber to be introduced. Additionally, there is a motor which vibrates to minimize the speckle noise. The S21 is measured using the Vector Network Analyzer VNA E5071C from Agilent. The RF output of the VNA was used to modulate the laser and the RF output of the receiver SPD-2_650 (SPD) from Graviton to the VNA.

Now the common attributes of both configurations are established, it is time to talk about the differences among the configurations. The key detail that differentiates the OF from UF is the integration of a very short fiber with a scrambler on the OF configuration. The scrambler has the effect of coupling light to higher angles creating the desired OF launching conditions [3]. As POFs are known for the high variability of their properties, we designed a robust procedure to measure all three characteristics including optical power, FFP, S21 parameters [4].

The experimental characterization protocol was the following. First, we set the under-filled launching configuration with the V-SMF and the S-SMF connected to the test fiber. Then the FFP was observed to assure that UF conditions have been achieved, The FFP was recorded and saved, and the S21 parameter was obtained with the VNA. Then, the OF launching configuration is set by connecting the 1-m POF with the scrambler between the S-SMF and the tested POF, and the same properties are measured but in a different order. At the end of the protocol, the test fiber was removed allowing the measurement of the S21 parameter for the back-to-back system (B2B). B2B is measured connecting the transmitter and the receiver with a very short fiber (1-m GH) whose attenuation and dispersion are negligible. Thus, the B2B S21 is used to account for the effects of the opto-electronic components over the frequency properties.

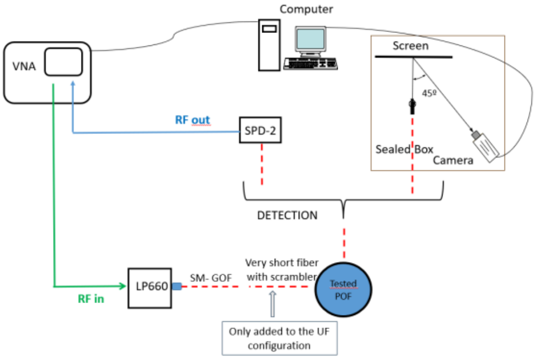


Fig. 1. Experimental set-up

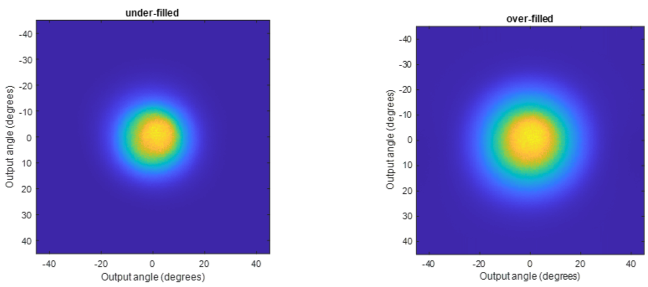
III. Results and Discussion

This section is organized into three different subsections to display and discuss the results obtained applying the experimental protocols described above. First, we compare the transmission properties of UF and OF launching conditions for a 15 m SI-POF. Then, we compare two different fiber lengths under the described launching conditions. Third, we investigate how the launching conditions impact on the GI-POF and compare these results to those obtained for the SI-POF.

A. 15-meter SI-POF

In this subsection, we show transmission properties of a 15-meter SI-POF fiber under UF and OF launching conditions. The spatial properties of light at the output of the fiber were characterized in terms of encircled angular flux (EAF) obtained from the FFP images, whereas the frequency response of the fiber was obtained from the measurements of the S_{21} parameter for the system and the B2B. Finally, fiber 3-dB bandwidth, and EAF width were obtained from the fiber amplitude frequency response and from the EAF, respectively to evaluate the influence of the launching condition.

The FFP images of the 15-meter fiber are shown in Figure 2 for both launching conditions, as a function of the output angle in degrees. It is clear how the UF conditions show a narrower pattern than the OF condition even after 15-m fiber transmission. The EAF obtained from the measured output FFP is a suitable way to present the spatial distribution of optical power by representing the portion of power contained within a specific solid angle. Thus, Figure 3 displays the EAFs obtained from these measurements.



(a) (b)

Fig. 2. FFP images at the output of a 15-m SI-POF for the selected launching conditions: (a) UF, (b) OF.

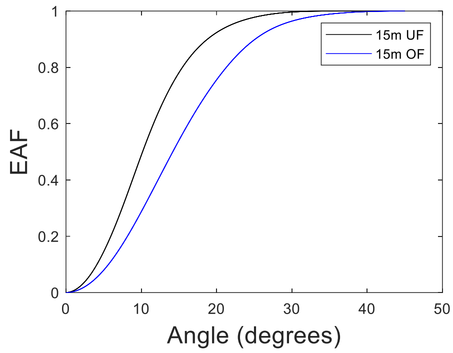


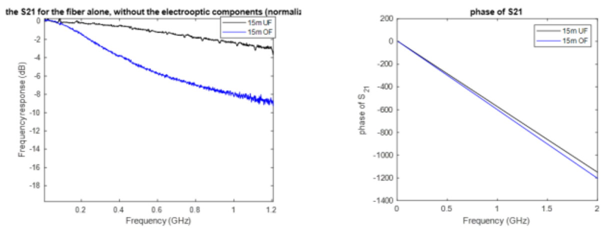
Fig. 3. Comparison of EAF between OF and UF launching conditions for a 15-m SI-POF.

The graphs illustrate the different behavior of the fiber under the different launching conditions. As the FFP images show, the UF injection produces a narrower spatial distribution than the OF injection. This is confirmed by the EAF, whose widths at half maximum (50% EAF) were equal to 10.17°, and 14.18° for UF and OF, respectively.

The fiber frequency response was obtained from the measurements of the S_{21} transmission parameters for the system with the fiber and the B2B according to:

$$H_{POF}(f) = \sqrt{\frac{|S_{21,L}(f)|}{|S_{21,REF}(f)|}} \qquad (1)$$

where $S_{21,L}(f)$ is the link transmission parameter measured for a fiber length, and $S_{21,REF}(f)$ is the transmission parameter for the B2B (obtained with the 1-m POF). The very short fiber segment was used as a reference to obtain the frequency response of the complete link without the fiber. The frequency response obtained in this way only represents the effects introduced by the fiber itself without those of the active devices. The magnitude and phase of the frequency response of the different conditions are represented on the left, and right plots of Figure 4, respectively.



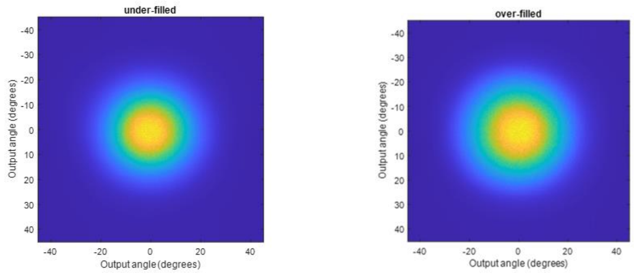
(a) (b)

Fig. 4. Comparison between frequency response obtained with UF and OF launching conditions: (a) magnitude, (b) phase.

The frequency response of the fiber under overfilled injection is lower than the fiber frequency response under under-filled injection. The reason is that in the overfilled launching condition, light is injected into the fiber at high propagation angles, increasing modal dispersion, which degrades the frequency response. As can be observed, there is a slight difference in the slope of the phase of the frequency response between the UF and OF launching conditions. However, this difference is not related to differences in transmission between the two launching conditions, but to the differences in the experimental set-up. The main difference between both configurations is an addition of an extra 1-m of POF, which implies an extra delay of about 4 nanoseconds. As a result, we did not found measurable differences in the slopes of the frequency response phase due to the different launch conditions.

B. 15-meter and 30-meter SI-POF

In this subsection, we compare the effect of the launching conditions for two different fiber lengths by considering two segments of the GH SI-POF: 15 meters and 30 meters. Figure 5 shows the FFP images at the output of the 30-meter fiber under test for the UF and OF conditions.



(a) (b)

Fig. 5. FFP images at the output of a 30-m SI-POF for the selected launching conditions. (a) UF, (b) OF.

As can be seen, the FFP image corresponding to the OF condition of the 30-m fiber is only slightly wider than the UF FFP of the same length. To compare all the conditions, we extracted the EAF curves from the measured FFP images for the 30-m fiber and plotted them together with the curves obtained before for the 15-m fiber. Results are shown in Figure 6.

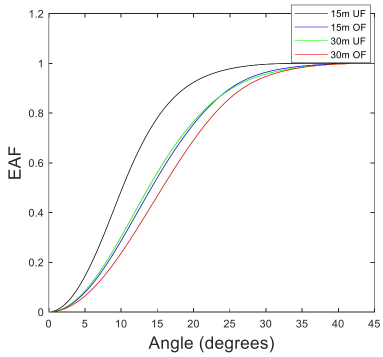


Fig. 6. EAF graph for 15 meter and 30-meter SI-POFs with UF and OF launching conditions.

From the Figure above, we can observe that the EAF of the 30-m fiber under UF condition is narrower than the EAF of the 30-m fiber under OF condition, but this difference is reduced compared to the 15-m fibers. Thus, our results show that the impact of launching conditions is more evident in shorter fibers than in longer fibers. To analyze some numbers and to prove the concept, we calculated EAF width at half maximum as can be found in Table 1, including the values obtained for 15-m.

Table.1. Angle at 50% of EAF for 15 m SI and 30 m SI fiber.

Angle at 50% EAF				
Length/Configuration	15m UF SI	15m OF SI	30m UF SI	30m OF SI
Angle [°]	10.17	14.18	13.76	15.69

While for 15.m, the difference in 50% EAF angle is 4 degrees, for 30-m it is reduced to just 2 degrees. It is evident that the difference in EAF between OF and UF is reduced when increasing the fiber length. In fact, it is well-established that as light propagates through the POF, its modal distribution widens until it reaches its steady state (SS). If the fiber length considered is equal or greater that the length for SS, the influence of the launching condition may be ignored [3]. According to the EAF results in Figure 6, we can conclude that 30 meters is still below the SS length for this SI-POF, but close to it.

The magnitude and phase of the frequency response were obtained, but we found out that the launching conditions don't have influence on the phase, so we showed only the magnitude of the frequency response as shown in Figure 7.

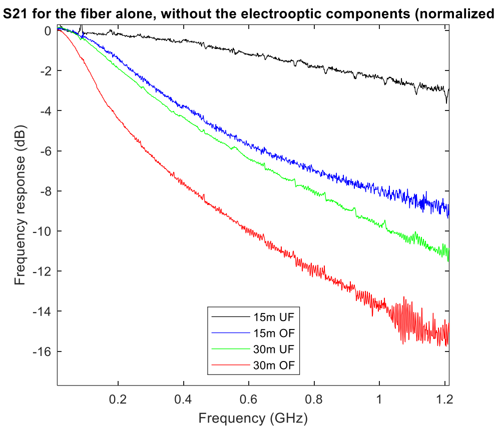


Fig. 7. Magnitude of S21 for 15 meter and 30-meter SI POFs with UF and OF launching conditions.

These results reveal that frequency response of the 30 m fiber with UF injection is better than the frequency response of 30 m and OF injection. This difference, however, is not as large as that obtained for the 15m fiber, also represented in Fig. 7, but still noticeable. From the frequency responses, the 3-dB bandwidths are calculated for both lengths under the two described launching conditions and shown in Table 2.

Table 2. 3dB bandwidths for 15 m SI and 30 m SI fiber.

Fiber at 3db Bandwidth				
Length/Configuration	15m UF SI	15m OF SI	30m UF SI	30m OF SI
Frequency [GHz]	1.1095	0.3160	0.2849	0.1418

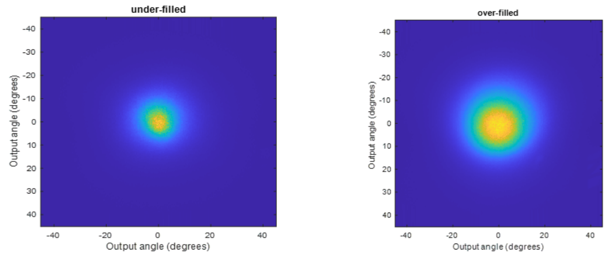
These data proves that fibers of the same length exhibit wider bandwidth with UF launching conditions. The bandwidth difference between the two launching conditions is larger for shorter fibers.

C. Comparison of 15-meter GI-POF 15-meter SI-POF

In this subsection, we aim to explore the transmission characteristics of a 15-meter GI-POF as we change the launching conditions and to conduct a comparative analysis between the 15-meter SI-POF and the 15-meter GI-POF.

We obtained the FFP images of 15-m GI fiber, the EAFs, and the frequency responses, under the two different conditions with the same experimental protocol described above.

Figure 8 shows the FFP images of a 15-m GI-POF under UF and OF launching conditions.



(a) (b)

Fig. 8. FFP images at the output of a 15-m GI-POF for the selected launching conditions. (a) UF, (b) OF.

Again, the FFP image for OF launch is wider than the one obtained with UF launch. Also, both are smaller that those obtained for the SI-POF of 15-m. This is more clearly visualized with the EAF curves of the 15-m GI-POF under the described launching conditions, shown on the same graph as the EAFs for the 15-m SI_POF for the sake of comparison in Figure 9.

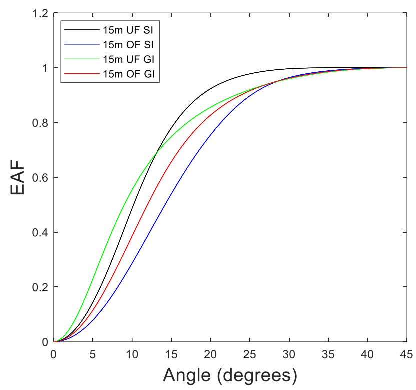


Fig. 9. EAF for 15-meter SI and GI fiber with UF and OF launching conditions.

To better quantify the differences and make a proper comparison, we included EAF width at half maximum values in Table 3.

Table 3: Angle at 50% of EAF for 15 meters SI and GI fiber.

Angle the has 50% of the EAF				
Length/Configuration	15m UF SI	15m OF SI	15m UF GI	15m OF GI
Angle [°]	10.17	14.18	8.99	11.94

From these results, it can be concluded that UF and OF launching conditions affect both 15-m SI- and GI-POFs but have a greater influence on the SI-POF.

The magnitude and phase of the frequency response were also obtained for the 15-m GI-POF. We found out that there is no difference in the phase of the frequency response when changing launching conditions and thus, we only represent the magnitude of the frequency response in Figure 10 for the 15-m GI-POF and the 15-m SI-POF, normalized to 1 to facilitate comparison.

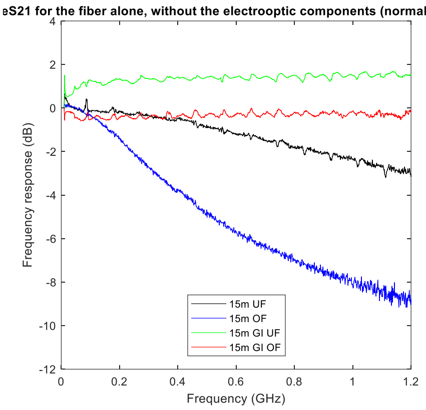


Fig. 10. Magnitude of S_{21} for 15meter SI and GI POFs with UF and OF launching conditions.

After subtracting the frequency response of the B2B from the frequency response of the system, it was found out that the frequency response of the 15-m GI-POF is almost flat. This means that 15-m GI-POF is similar to the reference (B2B) which implies that the GI-POF does not introduce further degradation to the optoelectronic system. For illustration, we represent in Figure 11 the magnitude of the S21 parameters for the B2B (short fiber), and for the overall system including the 15-m GI-POF under both launching conditions. It can be seen that the frequency response of the 1-meter fiber is almost identical (apart from a vertical shift) to the frequency response of the system when we used 15-m GI-POF with both launching conditions. These results demonstrate that the graded index profile is very effective in reducing modal dispersion and increasing bandwidth. The 3dB bandwidth for the GI-POF cannot be obtained, as the fiber frequency response is flat. We can only tell that fiber bandwidth is greater than 2-GHz for 15-m. In fact, the system performance is limited by the characteristics of the opto-electronic components of the link [5].

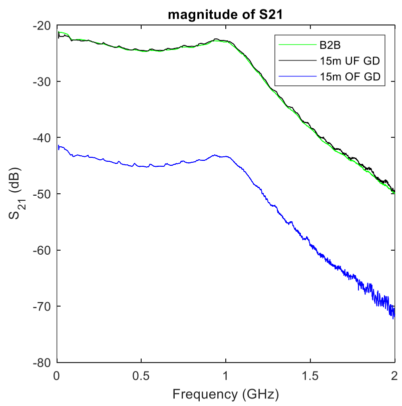
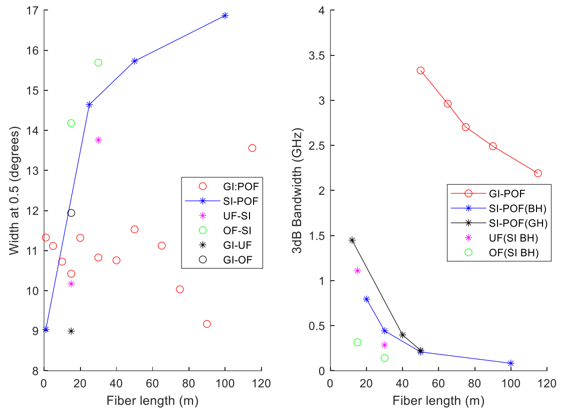


Fig. 11. Magnitude of S_{21} parameter: the magnitude of S_{21} parameter of 1-m fiber (B2B), the system with OF launch, the system with UF launch,

In order to have a complete picture of the results presented in this paper, our results should be compared with data obtained previously. Figure 12 shows 3-dB bandwidth and angle that has 50% of the EAF of GI-POF, SI-POF (BH), SI-POF (GH), under-filled values, and overfilled values as function of length. It is important to note that SI-POF (BH) was used in our experiment.



(a) (b)

Fig. 12. Data obtained previously (a) 3-Bb bandwidth, and (b) EAF width at half height as a function of fiber lengths. [5]

Figure 12a shows the angle that has 50% of the EAF values and it is for 15-m SI fiber is around 12°, 15° for 30-m SI fiber, and 10.4° for 15-m graded index. These values can be compared to the values that we obtained and shown in the same graph. The graph shows that the UF values that we obtained are less than the values that were obtained previously, and the OF values that we obtained are larger than the values that were obtained previously.

Figure 12b shows the 3dB bandwidth values obtained previously. The 3-dB bandwidth of 15-m BH SI fiber was not obtained, but it was equal to 0.44 GHz for 30-m SI fiber. By comparing these values to our values, we can notice that these values are close to the UF values, but they differ from OF values because OF configuration shows a degraded frequency response and lower 3-dB bandwidth values as discussed before. Also, 3-dB bandwidth values of 40-m GI fiber or shorter could not be obtained and aren't shown in figure 12a, which agrees with the flat frequency response that we obtained for 15-m GI POF.

IV. Summary and Conclusion

We confirmed that the impact of the launching condition is more noticeable in shorter fibers. Our data showed that the difference in the spatial distribution of optical power between OF and UF launching conditions is more noticeable when we tested the 15 m-fiber, however the impact of the different launching conditions still exists for the 30-m fiber. Furthermore, our data showed that the type of launching condition also has impact on the optical power distribution of GI-POFs, but we were not able to obtain differences between the GI-POF frequency response for the two launching conditions due to our experimental set-up limitations and the frequency response was measured within the range of 0 to 2 GHz. These results were expected because graded index fibers were designed to reduce model dispersion and allow higher transmission bandwidths especially for shorter lengths. For the SI-POF, however, we found that the frequency response is better with UF launching conditions than with OF launching conditions, resulting in a larger 3dB bandwidth. The over-filled injection set-up consists of a scrambler which increases modal dispersion because it excites higher order modes and limits the bandwidth. The frequency response of the 15-m GI-POF is almost flat, consequently with its reduced modal dispersion. We could not find any difference between the phase of the frequency response between OF and UF conditions in any of the fibers/lengths tested. We conclude that the launching conditions can play an important role especially for shorter SI-POFs and that applying UF condition can lead to increase their transmission rates [6].

V. Acknowledgment

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