Misalignment Losses in Step-Index Multicore Plastic Optical Fibers

Amaia Berganza, Gotzon Aldabaldetreku, Joseba Zubia, Gaizka Durana, and Jon Arrue

***Abstract*—We analyze the extrinsic coupling losses due to misalignments in three different SI-MCPOFs. Four kinds of misalignments are analyzed: longitudinal separation, transversal offset angular misalignment and rotational misalignment. We have performed experimental measurements and complementary computational simulations to assess the effect of misalignments and the influence of crosstalk and fiber characteristics on coupling losses.**

***Index Terms*—Geometric optics, loss measurements, optical fibers, optical losses, ray tracing.**

I. Introduction

MULTICORE plastic optical fibers (MCPOFs) constitute a good alternative to conventional single-core-POFs due to their smaller sensitivity to bending losses and their large size. These fibers are composed of small cores embedded in a cladding material. As a whole, the cores cover the same large diameter as a conventional POF and, consequently, the advantages of POFs are maintained, whereas bending losses are reduced [1], [2]. Due to such properties, MCPOFs in combination with VCSEL are becoming more and more attractive for Fiber To The Home (FTTH) and Fiber To The Building (FTTB) and short-reach optical interconnection applications where they are used as conventional single-core SI POFs, with a higher bandwidth and lower losses[3]–[5]. But they can also be used to transmit different channels using a different core for each channel. In this case, single model fibers (SMFs) and lenses could be used as light source, as well as VCSELs [6], [7].

In all these applications misalignments can occur when two MCPOFs are connected, which causes additional coupling losses.

In standard single-core optical fibers, three kinds of misalignments may occur: longitudinal separation, transversal offset and angular misalignment [8]. However, when dealing with MCPOFs a new kind of misalignment appears: the rotational misalignment. That is to say, if the cores in the cross sections of the transmitting and receiving fibers are not properly aligned, part of the power is lost in the junction.

In a previous work, we measured coupling losses in perfluorinated graded-index (GI) multicore fibers [9]. In this paper, our purpose is to complete that study by analyzing three different step-index (SI) MCPOFs, to explore the behavior of these fibers and the influence of the number of cores on coupling losses. Furthermore, measurements of rotational misalignments are included which, as far as we know, have never been carried out. Finally, we discuss the influence of crosstalk (denoted by the abbreviation XT) and fiber characteristics on coupling losses using the results obtained by accurate experimental measurements and completed by additional computational simulations.

The structure of the paper is as follows. First, we introduce the SI-MCPOFs studied in this work. Then, the experimental set-up used to perform the measurements is explained. Afterwards, we describe the simulation conditions. Next, the results obtained by the experimental measurements and simulations are analyzed and discussed. Finally, we summarize the main conclusions.

II. Characteristics of the Different SI-MCPOFs Analyzed

In order to observe the influence of fiber characteristics on coupling losses, we have studied three different SI-MCPOFs developed by Asahi Kasei [10]. In these fibers, the cores are arranged in concentric rings around a central core and the numerical aperture and the cladding radius are 0.6 and $500\mu\mathrm{m}$, respectively. We have employed a 19-core-MCPOF, a 37-core-MCPOF and a 217-core-MCPOF with mean core radii of $97\mu\mathrm{m}$, $66\mu\mathrm{m}$ and $27.5\mu\mathrm{m}$, respectively. Fig. 1 shows the cross sections of the investigated fibers. It must be pointed out that the cores in these fibers are not circular, but rather polygonal, due to some unknown effect during the manufacturing process [2]. This effect makes the total area covered by cores larger than in the ideal case of perfectly circular cores, which leads in most cases to more favorable conditions with regard to misalignment, as will be seen later in this paper.

Because of these irregularities, the minimum separation distance between cores is different in the real case and the ideal one as can be seen in Table I. These discrepancies lead to different fill-factors (area covered by cores/total area), as is shown in Table II.

III. Measurements

A. Experimental Measurements

Fig. 2 depicts the experimental set-up used to measure coupling losses in MCPOFs due to misalignments.

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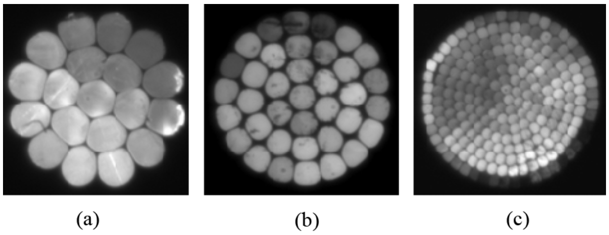

Fig. 1. Cross sections of the investigated fibers: (a) 19 core MCPOF; (b) 37 core MCPOF; (c) 217 core MCPOF.

TABLE I
MINIMUM SEPARATION DISTANCE BETWEEN CORES IN REAL AND IDEAL SI-MCPOFs

	19-core-MCPOF	37-core-MCPOF	217-core-MCPOF
Real fiber	7-8.5 µm	10-15 µm	3-5 µm
Ideal fiber	7.5 µm	12.66 µm	4.06 µm

TABLE II
FILL-FACTOR OF REAL AND IDEAL SI-MCPOFs

	19-core-MCPOF	37-core-MCPOF	217-core-MCPOF
Real fiber	79 %	81.9 %	85.1 %
Ideal fiber	71.5 %	64.5 %	65.6 %

We employ a 594-nm-wavelength 10 mW He-Ne laser followed by two lenses, L1 and L2, which are used for expanding the laser beam so as to cover the whole aperture of the object lens placed following the beam splitter. In this way, we ensure that the whole numerical aperture of the object lens $(\mathrm{NA} = 0.65)$ is covered and, consequently, all modes in the MCPOFs are excited. The spot size at the input surface of the MCPOFs is $7 \pm 1 \mu\mathrm{m}$. We use lenses L3 and L4 for magnification. An attenuator is employed in order to avoid saturation of a camera (CAM1) that is used to check that the transmitting fiber is correctly placed on the focal distance of the objective. The XYZ micropositioner allows us to move the input surface of the transmitting fiber in order to achieve this placement. The transmitting fiber is a 1 m length straight section of SI-MCPOF (one of the three fibers shown in the previous section). Its end is placed on a rotational stage (RS) placed on top of two linear stages (LS1 and LS2). The linear stage LS1 is used to apply longitudinal misalignments (s) whereas LS2 is used to provide transversal offsets (d). The rotational stage is used to align the cross sections (which have been carefully polished) of the transmitting and the receiving fibers (since the polar angle that describes the angular orientation of the fiber with respect to a fixed reference direction defined in the cross section could be different in both fibers, it is important to align them in order to eliminate additional coupling losses due to a rotational misalignment) and to provide rotational misalignments. Cameras CAM2 and CAM3 are used to achieve the alignment of the transmitting and receiving fibers in both the horizontal and vertical planes. The receiving fiber is another 1 m straight section of SI-MCPOF. Its end is placed on an XYZ positioner located on an angular stage (AS) to provide

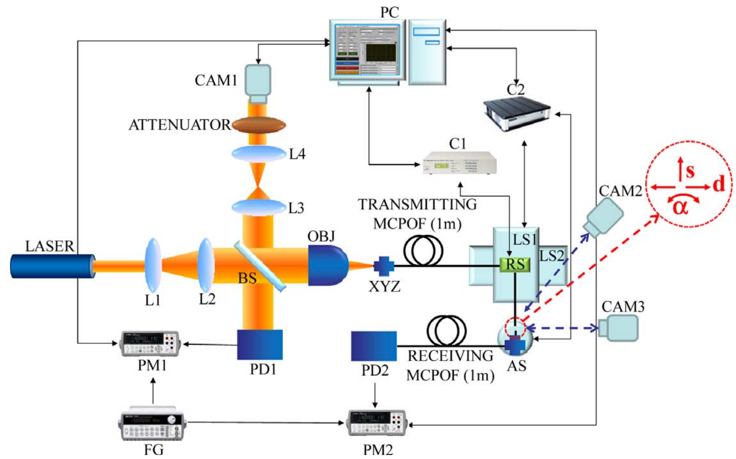

Fig. 2. Experimental set-up. Legend: L1: plane-concave lens $(f' = -40\ \mathrm{mm})$; L2: symmetric-convex lens $(f' = +150\ \mathrm{mm})$; L3: symmetric-convex lens $(f' = +150\ \mathrm{mm})$; L4 : symmetric-convex lens $(f' = +50\ \mathrm{mm})$; bs: beam splitter obj: 0.65-NA object lens; RS: rotational stage, LS1 and LS2: linear stages; as: angular stage; PM1 and PM2: power meters, PD1 and PD2: photodetectors; C1 and C2: controllers; XYZ: XYZ micropositioner; FG: function generator. s, d and a show the longitudinal, transversal and angular misalignments, respectively.

angular misalignments (α). The stages are operated by two controllers: C1 is an ESP300 (Newport) controller, which controls the rotational stage, and C2 is a corvus eco controller (Micos), which is used to handle the linear and angular stages. In order to measure the power at the end of the receiving fiber we use a photodetector PD2, 818-SL (Newport), connected to a power meter PM2, 34410A (Agilent), and, as a reference, we use the power measured by photodetector PD1, 818-SL (Newport), and power meter PM1, 34410A (Agilent). The power meters are connected to a function generator that provides an external trigger so as to obtain simultaneous measurements in both power meters. This is an important issue, as the output power of the He-Ne laser has significant short scale fluctuations which would cause additional errors in the measurements. By using an external signal that triggers both multimeters simultaneously, we ensure a perfect correlation between the power at the end of the receiving fiber and the reference power in each acquisition and, therefore, these additional errors are avoided. LabView is used in order to automate the measurements.

Measurements are performed in two different ways: (a) illuminating only the central core of the transmitting SI-MCPOF and (b) illuminating the whole endface of the transmitting fiber. The second case is achieved by inserting an additional standard single-core-POF between the objective and the transmitting MCPOF. Although the second launching conditions could be different from those employed in real applications (where LEDs are commonly used as light sources), illuminating the whole surface uniformly allows us to study the worst-case scenario, so the coupling losses obtained in our study could be used as an upper limit in real optical links.

In order to align correctly the cross sections of the transmitting and receiving fibers before applying any misalignment, we use the Hammamatsu LEPAS system. The procedure consists in illuminating only certain cores of the transmitting fiber, checking if those cores are illuminated by measuring the near field pattern with the LEPAS system placed at the end of the receiving fiber. If other cores are excited at that point, the rotational stage is employed to align both MCPOFs until the correct cores are illuminated in the receiving fiber.

The experimental set-up depicted in Fig. 2 is slightly changed to carry out the measurements of the coupling losses due to rotational misalignments. This modification is compulsory due to mechanical restrictions. In this case, the angular stage is removed and the rotational stage is moved to the place where the angular stage was.

B. Numerical Simulations

Apart from experimental measurements, we have carried out computational simulations in order to complement those measurements for a better understanding of the behavior of the studied fibers. Simulations are based on a ray-tracing model which takes into account crosstalk between adjacent cores in MCPOFs [11]. Therefore, they allow us to analyze the effect of crosstalk on coupling losses. Although crosstalk is not very high in the studied fibers due to their high numerical aperture (see [11]), it still has an influence on coupling losses. The ray-tracing model has been chosen because fibers under analysis are highly multimode [12].

Simulations are only considered as a first approach, since we have made two simplifying hypotheses: on the one hand, the simulated fibers have circular ideal cores, in contrast to the polygonal and irregular cores of the real fibers. On the other hand, mode coupling is not taken into account. This assumption has been made on the basis that fibers employed are not long enough to have high mode coupling because, when illuminating the SI-MCPOFs with a narrow beam, the far field pattern measured at the end of the fibers is still narrow. Additionally, the cladding of the fibers is assumed to be unbounded.

In order to have the same initial conditions, simulations have been carried out in such a way that the near-field-pattern obtained at the output surface of the transmitting fiber resembles the corresponding experimental near-field-pattern.

The steps used in the simulations are 40 μm, 6 μm and 1° for the longitudinal, transversal and rotational misalignment, respectively because they are enough to appreciate the small variations of the coupling losses.

IV. Results and Discussion

A. Longitudinal Misalignment

Fig. 3(a) depicts the experimental coupling losses due to longitudinal misalignments when only the central core of the fibers is illuminated. The step size used is 20 ìm and, for the sake of comparison, all the misalignments have been normalized to the common cladding radius $r_{\rm cl}$. Each measurement has been made three times and the corresponding mean value and the uncertainty have been calculated.

It can be seen that, when the longitudinal separation is lower than 1.3, coupling losses are quite low for the 217-core-MCPOF and the 19-core-MCPOF. This is due to the fact that, although the laser beam is expanded because of the separation, all the power remains inside the input endface of the receiving fiber

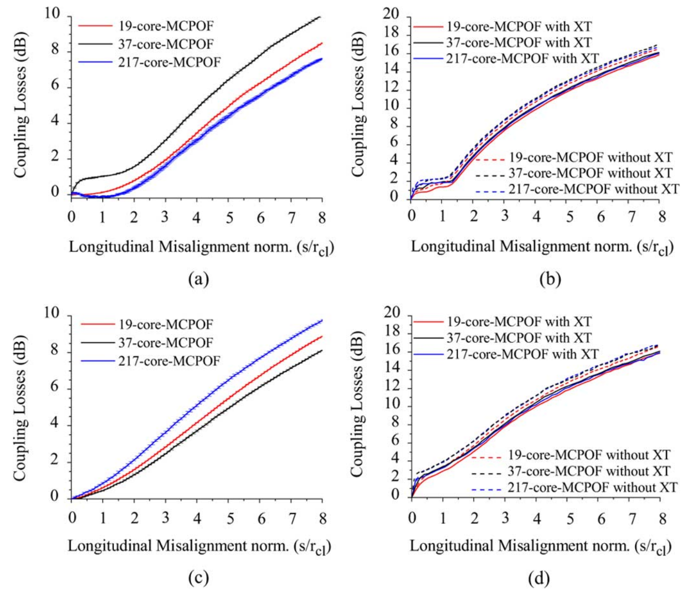

Fig. 3. Coupling losses due to longitudinal misalignment (s). (a) experimental results when exciting only the central core of the MCPOFs; (b) simulation results when exciting only the central core of the MCPOFs (dashed lines show the results obtained taking into account crosstalk among cores); (c) experimental results when illuminating the whole input endface of the MCPOFs; (d) simulation results when illuminating the whole input endface of the MCPOFs (dashed lines show the results obtained taking into account crosstalk among cores). bars in experimental results denote uncertainty.

and, consequently, it is collected by surrounding cores. This fact also occurs for the 37-core-MCPOF but, in this case, higher losses are observed. This is explained by the higher distance between cores in the cross section of this fiber in comparison with other MCPOFs (refer back to Table I), which makes it more similar to the ideal simulated fibers. In fact, simulation results in Fig. 3(b) allow us to confirm this explanation, as the distance between cores in the cross section is higher in all ideal simulated fibers and, consequently, higher losses are observed in all cases. Besides, in the case of the ideal 37-core-MCPOF, the separation distance between cores is higher than in the other ideal fibers and, as a result, coupling losses are higher (see Fig. 3(a)).

When s is higher than 1.3, coupling losses increase rapidly, as power is lost out of the endface of the receiving fiber.

Fig. 3(c) depicts coupling losses due to longitudinal misalignment when the whole endface of the transmitting fiber is illuminated. In this case, coupling losses increase in a monotonous way because part of the power is lost out of the endface of the receiving fibre even when the longitudinal separation is small. Therefore, coupling losses due to small misalignments are now higher than when only the central core is excited.

On the other hand, the fiber with the highest coupling losses is the 217-core-fiber, whereas the one with the lowest losses is the 37-core-MCPOF. This could be explained by the different shape of the cores in the real fibers, specifically by the shape of the more external cores. As all the cores in the fiber are excited, the shape of external cores becomes more important than when only the central core is illuminated. In Fig. 1 we can see that the most external cores in the 19-core-MCPOF are more deformed than the inner ones. In the case of the 217-core-MCPOF, they are more damaged. However, the shape of external cores in the

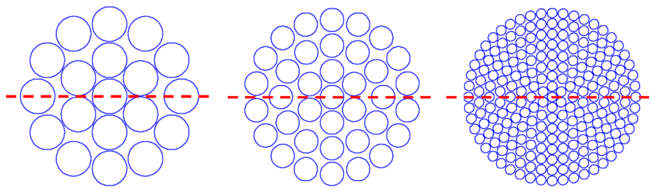

Fig. 4. The dashed red lines specifies the axis used to measure transversal misalignments for: (a) the 19 core MCPOF, (b) the 37 core MCPOF and (c) the 217 core MCPOF.

37-core-MCPOF (See Fig. 1) is more similar to that of the inner cores, since they are less deformed and damaged and, consequently, the transmission inside them is better. This effect is not observed in the simulation results, as, in this case, all the cores are ideal.

In Fig. 3(d) we can see that simulated coupling losses, are higher than in the experimental results when the longitudinal separation is small. This is because of the different fill-factors in ideal and real fibers (see Table II), so the cores in real fibers are packed closer together (see Table I).

Both when illuminating only the central core of the transmitting fiber and when exciting the whole endface, coupling losses are lower when crosstalk is taken into account than when it is not. This is due to the fact that, when power transfer between cores occur, the light tends to concentrate in the center of the transmitting fiber (in the central core and in the cores of the first surrounding ring) and also in the symmetry planes of the fiber, as it is explained in [11]. Because of this power distribution, coupling losses due to longitudinal separation decrease.

B. Transversal Misalignment

In this section, we show the results obtained when measuring coupling losses due to transversal misalignments ($\boldsymbol{d}$). The axis along which transversal offsets are carried out is the one depicted in Fig. 4, as this is the worst case when this kind of misalignment is applied. The step used in the experimental measurements is $10\mu\mathrm{m}$ for the 19-core-MCPOF and the 37-core-MCPOF, and $5\mu\mathrm{m}$ in the case of the 217-core-MCPOF. We have chosen different steps in each case because of the different core radii of the MCPOFs. That is to say, the smaller the core radius is, the smaller the step has to be in order to observe the short scale variation of coupling losses with the transverse offset.

In Figs. 5(a) and 5(b), it can be seen that, when only the central core is excited, there are some characteristic local maximum and minimum values. For instance, in the case of the 19-core-MCPOF, we can see two local minima (apart from the one corresponding to no misalignment, i.e., $d/r_{cl} = 0.0$), which happen when the normalized transverse offset is around ± 0.8. This is due to the fact that, at that point, a core in the second ring is being illuminated, i.e., all the power is recovered by that core instead of being lost into the cladding material. Notice that the normalized separation between the center of the central core and the center of one core placed in the second ring is given by (1) where i is the index that specifies the ring number in the fiber, r_{co} the core radius, r_{cl} the cladding radius and min_sep the minimum separation between cores (see Table I), which is calculated using (2) where n is the number of rings in the fiber.

$$\frac{i\,(\text{min\_sep} + 2r_{co})}{r_{cl}} = 0.806 \tag{1}$$

$$\text{min\_sep} = \frac{r_{cl} - (2n+1)\,r_{co}}{n}. \tag{2}$$

In the case of the 37-core-MCPOF, we find those minima around ± 0.58. Finally, for the 217-core-MCPOF, we can see four local minimum values around ± 0.24, ± 0.47, ± 0.7 and ± 0.945, corresponding to cores in the second, fourth, sixth and eighth rings, respectively (see Fig. 5(a)). In the experimental results, it is noted that these local minimum values do not always correspond to 0 dB, as they do in the simulations, because of the irregular shape of the cores, which produces mismatches in the area covered by each core, leading to higher losses [13], [14]. Therefore, depending on the number of cores of the fiber and on the axis of the fiber where transversal offsets are applied, coupling losses will show different minimum and maximum values.

Again, when crosstalk is taken into account, coupling losses are lower. Crosstalk makes tunneling rays attenuate faster causing a higher concentration of power in the center of the cores [11]. This fact leads to a smaller sensitivity to transversal misalignments.

When the whole endface of the transmitting fiber is excited, losses are more similar in all SI-MCPOFs, both in experimental and in simulation results. However, in the latter case we can see some local minimum values which appear at different transverse offsets, depending on the number of cores of the MCPOFs. Experimental results only show this behavior in the case of the 37-core-MCPOF, i.e., the fiber whose cores are more similar to ideal ones. Therefore, in comparison with simulation results, we can say that local minimum values are more clearly observed when cores are more circular and, consequently, there is more cladding material between them. However, when cores are polygonal and the separation between them is minimized, those minima are masked.

On the other hand, when the transversal offset is high, the 37-core-fiber has lower coupling losses than the other fibers, as the most external cores of this fiber are less deformed and damaged than the external cores of the other fibers, as we have explained in Section IV-A.

C. Angular Misalignment

Fig. 6 depicts coupling losses against angular misalignments. The step size used is 0.1°. In this case, losses are much lower than when longitudinal or transversal misalignments are applied. Differences between the 19-core-MCPOF and the 217-core-MCPOF are not meaningful. Just in the case of the 37-core-MCPOF, coupling losses are a little higher when angular misalignment increases, due to the higher separation between cores in this fiber. These results could be due to the different geometries of the cross sections of the fibers and to small differences in the NA.

Simulation results, as in previous cases, predict slightly higher coupling losses (around 0.05 dB higher) but they are not included because they do not contribute to additional conclusions or a better understanding of the behavior of coupling

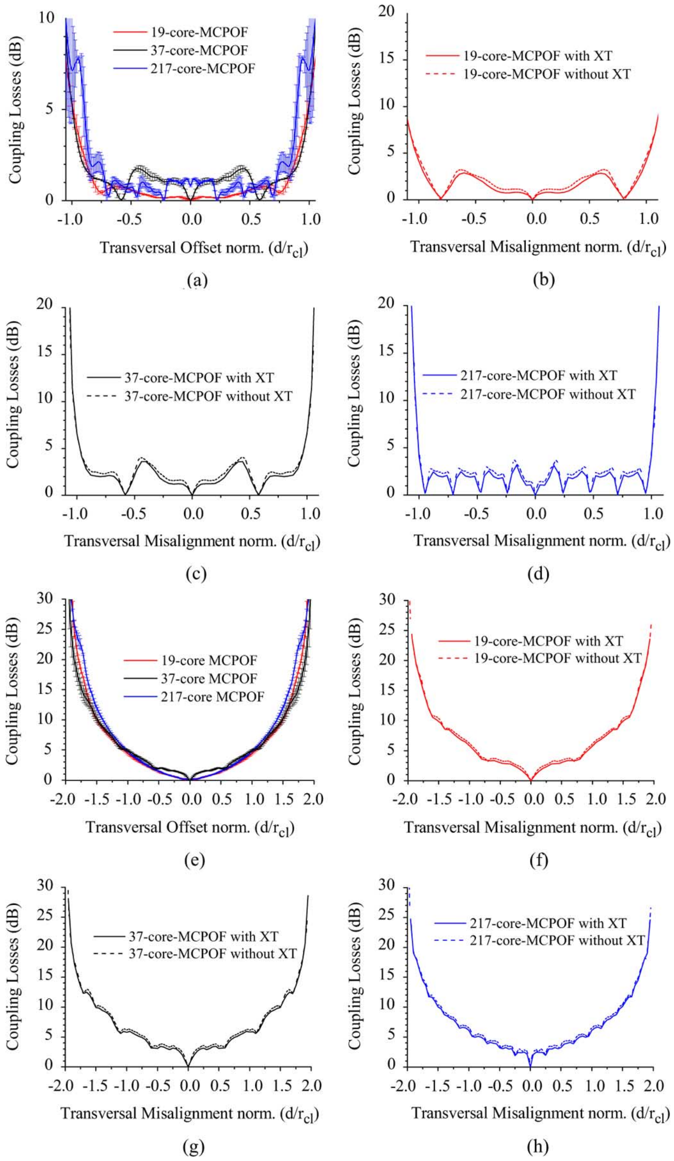

Fig. 5. Coupling losses due to transversal misalignment (d). (a) Experimental results when exciting only the central core of the MCPOFs; Simulation results when exciting only the central core of the: (b) 19 core MCPOF, (c) 37 core MCPOF and (d) 217 core MCPOF; (e) Experimental results when illuminating the whole input endface of the MCPOFs; Simulation results when illuminating the whole input endface of the: (f) 19 core MCPOF, (g) 37 core MCPOF and (h) 217 core MCPOF Bars in experimental results denote uncertainty.

losses due to angular misalignments since results are similar for all fibers.

D. Rotational Misalignment

In this section, we show the coupling losses when rotational misalignments between 0° and 30° are applied. We have chosen this range according to the symmetry of the cross-section of the fibers (see Fig. 1). That is to say, coupling losses when rotational misalignment varies from 30° to 60° are the same as the losses obtained when the misalignment varies from 30° to 0°. Therefore, when applying a misalignment of 60°, coupling losses are again 0 dB (in fact, a misalignment of 60° is equivalent to no rotation).

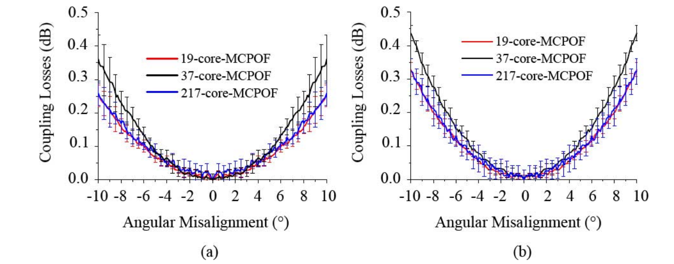

Fig. 6. Coupling losses due to angular misalignment (α). (a) Experimental results when exciting only the central core of the MCPOFs; (b) Experimental results when illuminating the whole input endface of the MCPOFs. Bars denote uncertainty (for the sake of clarity, we have only plotted every fifth error bar).

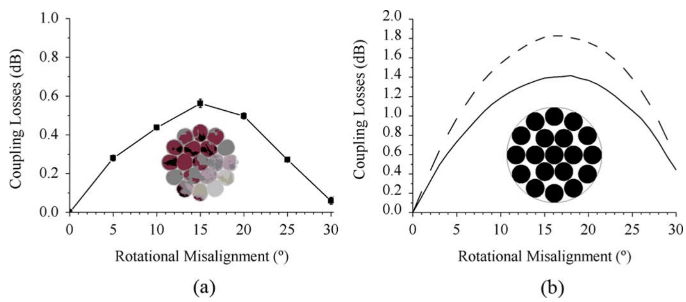

Fig. 7. Coupling losses due to rotational misalignments for the 19 core MCPOF; (a) Experimental measurements. The inset shows the cross section of the real fiber; (b) Simulation results. The dashed line corresponds to the simulation carried out without taking into account crosstalk between cores. The solid line corresponds to the simulation carried out taking into account crosstalk between cores. The inset shows the cross section of the ideal fiber.

Both experimental measurements and simulations have been carried out illuminating the whole endface of the transmitting fiber (when only the central core is illuminated there is no rotational misalignment). The step size used in the measurements is 5° due to mechanical restrictions.

Fig. 7 depicts the results obtained for the 19-core-MCPOF. Qualitatively, both experimental and simulation results agree quite well. However, there is a significant quantitative disagreement which could be explained by the difference between the fill-factors of the real and the ideal fibers. That is to say, since the fill-factor is higher in the real fiber because of the different shape of the cores compared to the ideal circular case, less power is lost in the cladding due to rotational misalignments. To remind the reader of this difference, the insets of each graph show the cross section of the corresponding fiber.

In Fig. 7(b) we can also see the effect of crosstalk on coupling losses (solid line). When crosstalk is present, coupling losses are lower than when it is not, due to the influence of tunneling rays, as happens when transversal misalignment occurs (refer back to Section IV-B).

Fig. 8 and 9 depict the results obtained for the 37-core-MCPOF and the 217-core-MCPOF, respectively. In these cases, simulations help us to see the short scale variations of the coupling losses with the rotational misalignment. That is to say, the information given by the experimental measurements, carried out with a larger step due to mechanical restrictions, is completed by simulations, made with a smaller step.

Experimental results allow us to quantify the importance of coupling losses due to rotational misalignment. As real fibers

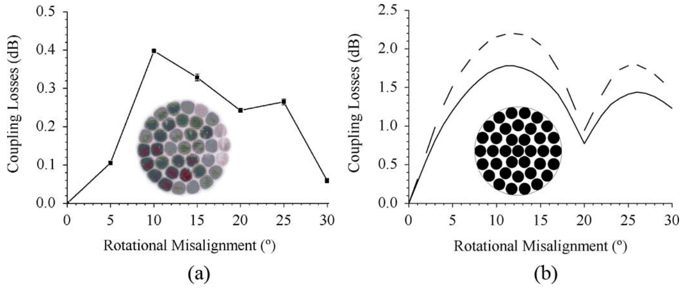

Fig. 8. Coupling losses due to rotational misalignments for the 37 core MCPOF. (a) Experimental measurements. The inset shows the cross section of the real fiber. (b) Simulation results. The dashed line corresponds to the simulation carried out without taking into account crosstalk between cores. The solid line corresponds to the simulation carried out taking into account crosstalk between cores. The inset shows the cross section of the ideal fiber.

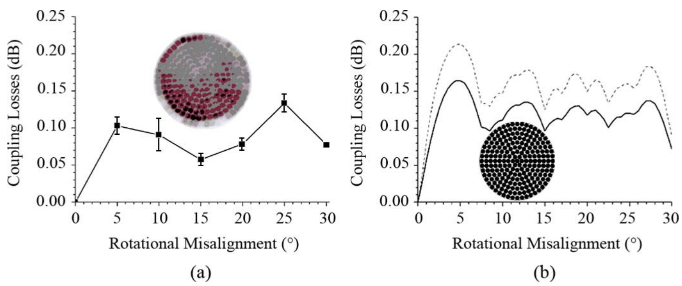

Fig. 9. Coupling losses due to rotational misalignments for the 217 core MCPOF. (a) Experimental measurements. The inset shows the cross section of the real fiber. (b) Simulation results. The dashed line corresponds to the simulation carried out without taking into account crosstalk between cores. The solid line corresponds to the simulation carried out taking into account crosstalk between cores. The inset shows the cross section of the ideal fiber.

have a higher fill-factor than ideal simulated fibers (see Table II), coupling losses are much lower in the experimental results than in the simulated ones. That is to say, the higher the fill-factor in real fibers is, the lower the coupling losses are (going from 79% in the 19-core-MCPOF to 85.1% in the 217-core-MCPOF, there is approximately a 0.3 dB decrease in the coupling losses). The same dependence with the fill-factor is observed in the simulations, where the lowest coupling losses correspond to the ideal 19-cores-MCPOF, which is the one with the highest fill-factor, whereas the highest losses refer to the ideal 37-core-MCPOFs, the one with the lowest fill-factor. However, in the simulations, this decrease is not as significant as in the real case. All in all, results suggest that the polygonal shape of real cores and the fill-factor are decisive parameters when dealing with rotational misalignments.

On the other hand, we can conclude that coupling losses are quite low when compared with losses due to longitudinal separation or transversal offset. In this sense, rotational misalignment is not a critical issue.

E. Combining Misalignments

1) Longitudinal Misalignment Versus Transversal Misalignment: We have seen that the most critical misalignments in SI-MCPOFs are transversal offset and longitudinal separation. Therefore, we have made additional experimental measurements combining these two kinds of misalignments, in order to study the longitudinal misalignment versus the transversal one. The step size used for the longitudinal separation is 100 ìm

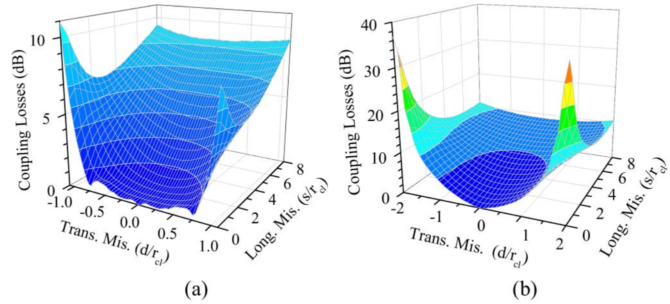

Fig. 10. Experimental measurements of coupling losses due to transversal misalignment versus coupling losses due to longitudinal misalignment for the 19 core SI-MCPOF; (a) when exciting only the central core of the MCPOFs; (b) when illuminating the whole input endface of the MCPOFs. For the sake of clarity, error bars are not depicted.

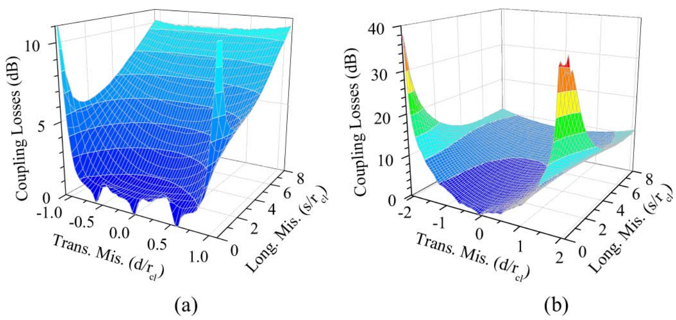

Fig. 11. Experimental measurements of coupling losses due to transversal misalignment versus coupling losses due to longitudinal misalignment for the 37 core SI-MCPOF; (a) when exciting only the central core of the MCPOFs; (b) when illuminating the whole input endface of the MCPOFs. For the sake of clarity, error bars are not depicted.

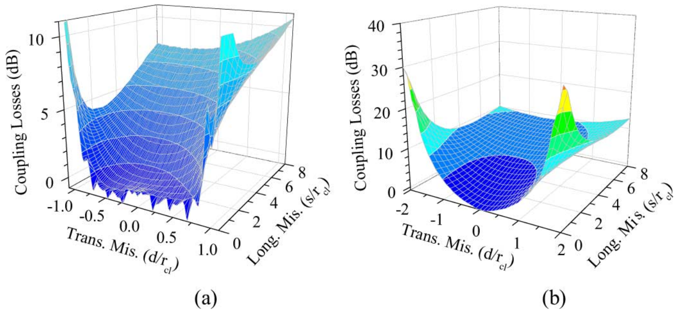

Fig. 12. Experimental measurements of coupling losses due to transversal misalignment versus coupling losses due to longitudinal misalignment for the 217 core SI-MCPOF; (a) when exciting only the central core of the MCPOFs; (b) when illuminating the whole input endface of the MCPOFs. For the sake of clarity, error bars are not depicted.

whereas the step for the transversal separation is 10 ìm. Results are shown in Figs. 10, 11, and 12. Each measurement has been made three times and its corresponding mean value and the uncertainty have been calculated ($\mathrm{uncertainty} = \pm 0.5$ dB) but, for the sake of clarity, the uncertainty is not depicted in Figs. 10, 11, and 12.

We can see that, when the longitudinal separation (s) is small, transversal misalignment (d) is much more critical than the longitudinal one. We can also see that, in this case, coupling losses can even decrease as the longitudinal separation increases. This is due to the fact that, when transversal offset is present and, as a consequence, the beam from the transmitting fiber illuminates a region between cores in the endface of the receiving fiber, increasing the longitudinal separation makes the cone of radiation to expand and illuminate not only the cladding region but also other cores around it.

On the other hand, as s increases, longitudinal misalignments become more decisive and the effect of the transversal misalignment is not so important.

Finally, we can observe that, when exciting only the central core of the MCPOFs, the characteristic minimum values disappear quite quickly as longitudinal separation increases. This is due to the divergence of the laser beam and the high fill-factors of real fibers which lead to the excitation of more than one core in the input endface of the receiving fiber.

V. Conclusions

We have studied coupling losses in SI-MCPOFs for different launching conditions and due to four kinds of misalignments: longitudinal, transversal, angular and rotational.

When dealing with transversal offset, the number of cores in an SI-MCPOF has an influence on the incurred losses, because, depending on its value, the position and the number of the local maximum and minimum values appearing in the coupling losses change. On the other hand, the shape of the cores is also decisive, and, therefore, the behavior of the 37-core-MCPOF is more similar to the ideal case. Due to this fact, the shape of the cores is an important issue that should be taken into account when manufacturing MCPOFs.

The number of cores is also an important parameter when rotational misalignments are applied. Increasing the number of cores in real fibers involves increasing the fill-factor which, at the same time, reduces coupling losses. Therefore, the fiber with the lowest coupling losses due to rotational misalignments is the 217-core-MCPOF.

In the case of angular misalignment, coupling losses are low in all cases, although in the case of the 37-core-fiber, they are a little bit higher due to the higher separation between cores.

Finally, when longitudinal misalignment is applied, the results depend on the launching conditions: if only the central core is excited, the lowest coupling losses correspond to the 217-core-MCPOF, whereas, when all the endface of the transmitting fiber is excited, the lowest coupling losses correspond to the 37-core-MCPOF.

We have also seen that the most critical misalignment is the transversal one, provided that the longitudinal one is not too high, whereas the angular and rotational ones are the less critical.

We can conclude that separation between cores, the fill-factor and the geometry of the cores are influential parameters when dealing with coupling losses.

The effect of crosstalk has also been analyzed and we have seen that, when power transfer between cores in an SI-MCPOF occurs, coupling losses tend to decrease. However, it is important to take into account that increasing the crosstalk has other negative effects as, for example, reducing the bandwidth.

Finally, it has been shown that, for certain values of transversal misalignment, increasing the longitudinal separation can provide partially lower coupling losses.

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