Relationship between Polarization Mode Dispersion and Crosstalk in Heterogeneous Multi-core Fibers with Different Cladding Diameters

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Abstract: We experimentally investigate the relationship between crosstalk and polarization mode dispersion (PMD) in two heterogeneous multi-core fibers with different cladding diameters. We observed that increasing the cladding diameter improves the crosstalk, but deteriorates the PMD.

1. Introduction

Multi-core fibers (MCFs) have been demonstrated to be a promising solution to overcome the inherent transmission capacity limit of single-mode fibers (SMFs) [1]. In particular, heterogeneous multi-core fibers (Hetero MCFs) have attracted the attention of researchers due to their capacity to suppress inter-core crosstalk (IC-XT) when bent past a certain critical value [2]. A recent study demonstrated that the XT of Hetero MCF is dependent on the cladding diameter of the fiber, where the larger it is, the better the XT [3]. One possible explanation to this dependence was attributed to the effects of random polarization-mode coupling that occur due to a difference in birefringence between the two fibers [4]. However, a topic that remains to be investigated is the polarization mode dispersion (PMD) dependence on the cladding diameter (CD) of Hetero MCF and how it compares to that of the XT.

This paper presents our results from investigating how both the PMD and XT are dependent on the CD of Hetero MCF. This was achieved by using a combination of experimentally measured and simulated values of PMD and IC-XT from two Hetero MCFs with almost identical cores, but different cladding diameter. The simulated values were obtained based on the birefringence beat length L_B and correlation length L_C of every core in both fibers. Results show that an increase in the CD improves the XT of a fiber, but deteriorates its PMD.

2. IC-XT and PMD with random polarization mode coupling

It is well known that the birefringence of an optical fiber changes randomly over time and that it is susceptible to structural perturbations [5,6], whether they are introduced on purpose or caused by any external factor. This random evolution of the birefringence can be characterized by using individual Ornstein-Uhlenbeck (O-U) processes [4] for each of the two orthogonal polarization-modes that travel through each core, as a function of two parameters: birefringence beat length L_B and its correlation length L_C. These are two key parameters that can be considered to analyze the effects of the birefringence at the time of performing XT or PMD simulations of a specific fiber.

In the case of simulating the XT performance of an MCF, coupled mode theory has been proven to be an accurate tool for this task [1]. A random phase noise model has been proposed that considers any noise introduced during the propagation as a function of the correlation length of the random phase function [7]. However, there are some cases where using this model can lead to some unrealistic values of correlation length [8]. Thus, for our investigation, we modeled the randomness introduced during the propagation of the light as a function of the changes in birefringence, which gives us two degrees of freedom, namely L_C and L_B, to characterize the IC-XT of an MCF, instead of only one as in the random phase noise model. The following modified coupled mode equation is used to consider the random polarization mode coupling in each core during the propagation [9]:

$$\frac{d\mathbf{A}_n(z)}{dz} = j\beta_n(z)\mathbf{A}_n(z) + j\sum_{n\neq m} \mathrm{K}_{nm}\mathbf{A}_m(z) + j\frac{\mathbf{B}_n(z)\cdot\boldsymbol{\sigma}}{2}\mathbf{A}_n(z) \tag{1}$$

where $\mathbf{A}_n$ is a vector of the complex mode amplitude in core n with components $A_{n,x}$ and $A_{n,y}$, β_n is the propagation constant in core n, K_{nm} is the mean coupling coefficient between cores n and m, $\mathbf{B}_n$ is the birefringence vector with components $B_{n,x}$ and $B_{n,y}$ obtained from the O-U process, and $\boldsymbol{\sigma}$ stands for the Pauli matrices. The z-component of the complex mode amplitude and the birefringence vectors are not considered since circular birefringence is almost negligible in standard telecommunication fibers [10].

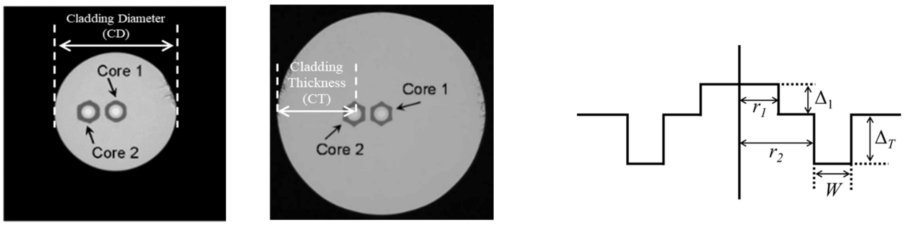
The PMD of each core in a fiber is also dependent on the birefringence parameters. The following equation can be used to calculate the PMD as a function of L_B and L_C [11]:

$$PMD = \frac{8}{\omega L_B}\sqrt{\frac{\pi}{3} L L_C} \tag{2}$$

where ω is angular frequency and L is the length of the fiber. For the purpose of our analysis, however, we considered the polarization mode dispersion coefficient D_{PMD}, which is equivalent to the PMD divided by the square root of the propagation distance. This phenomenon has been thoroughly investigated throughout the years in conventional SMF, but the PMD of every core in Hetero MCFs still has not received much attention. We expect that some parameters of the fiber, such as the cladding diameter and cladding thickness (CT) of each core, can have an impact on the correlation length of polarization mode coupling and ultimately end up affecting its PMD performance.

3. Evaluating the dependence on the cladding diameter

For our investigation we considered simulated and measured data from two different 2-core Hetero MCFs, shown in Fig. 1(a) and (b), with almost identical cores between them, but each has a different cladding diameter. Fiber 2CF-A has a CD of 134 μm, a core pitch of 29.9 μm, and a length of 3.5 km. Fiber 2CF-B has a CD of 229 μm, a core pitch of 29.7μm, and a length of 4.9 km. Both cores in each fiber are surrounded by a low-index trench layer with a relative refractive index Δ_T of –0.7%. The core refractive index profile and parameters are shown in Fig. 1(c) and Table 1, respectively. The simulations and measurements were obtained considering a bending radius of 155 mm, which is larger than the critical bending radius of 85 mm for both fibers, and a wavelength of 1.55 μm.



(a) (b) (c)

Fig. 1. Cross-section views of fibers (a) 2CF-A and (b) 2CFB, and (c) core refractive index profile [3].

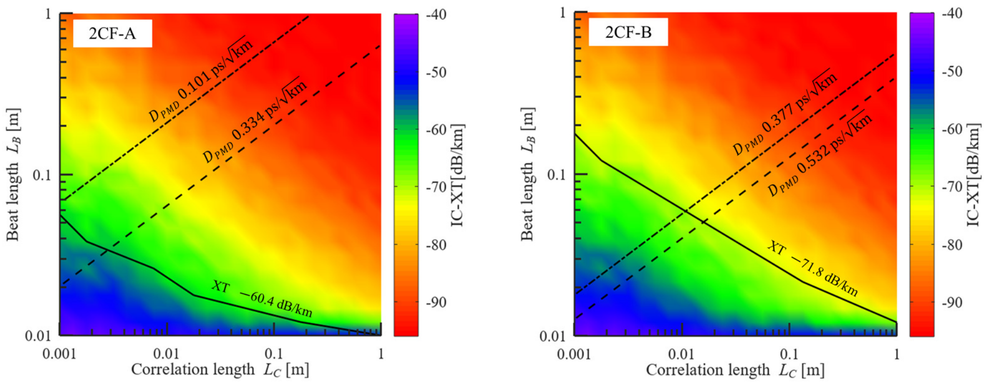
Table 1. Core parameters of 2CF-A and 2CF-B.

	r_1 [μm]	r_2/r_1	W/r_1	Δ_1 [%]
Core 1	4.62	1.7	1.0	0.305
Core 2	4.47	1.7	1.2	0.273

Table 2. Measured PMD coefficient D_{PMD}.

D_{PMD} [ps/$\sqrt{\text{km}}$]			
2CF-A		2CF-B	
Core 2	Core 1	Core 2	Core 1
0.101	0.334	0.377	0.532

The measured IC-XT for 2CF-A and 2CF-B are –60.4 dB/km and –71.8 dB/km, respectively. The measured values of D_{PMD} from all cores are shown in Table 2. Taking both these measurements as a reference, we also simulated the IC-XT and D_{PMD} of both fibers as a function of the random polarization mode coupling parameters L_B and L_C, using Eq. (1) for the IC-XT and Eq. (2) for the D_{PMD}. The results are shown in Fig. 2.

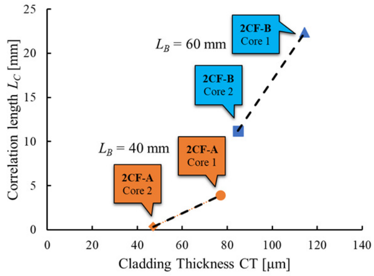


(a) (b)

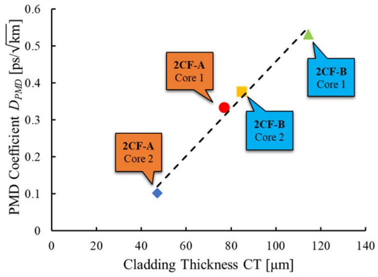
Fig. 2. Plot of the simulated and measured IC-XT and D_{PMD} of: (a) 2CF-A and (b) 2CF-B .

The colormap in Fig. 2(a) and (b) represents the results from simulating the IC-XT of both fibers. Since the core parameters are almost identical between the two fibers, the same colormap is used for the two of them. The continuous lines represent the measured XT, while the dashed lines and dashed-dotted lines represent the combination of L_B and L_C that result in the measured D_{PMD} of core 1 and 2, respectively. The simulated XT values were obtained from an average of 30/50/100 iterations, depending on the magnitude of L_C or L_B considered for every pair of points. In addition, we considered the same L_B and L_C values for both cores to simulate the XT. In reality, it is likely this is not the case, but we assume that as long both parameters are within the same order of magnitude, the results should serve as good reference of the expected behavior in practical fibers. It can be observed that when either L_B or L_C is increased, there is an improvement in the XT of the fiber, which is the expected behavior when considering Hetero MCFs bent past their critical value due to the reduced randomness introduced during propagation. On the contrary, based on Eq. (2), the PMD improves for smaller values of L_C and larger values of L_B.

The L_B and L_C of each core can be estimated based on the intersecting points between measured XT and D_{PMD} curves in Fig. 2. Doing so shows that all cores have a similar L_B in the range of 40–60 mm, while the L_C for each core can vary more from one core to another. In particular, Core 2 in 2CF-A seems to have the smallest values for this parameter. We assume this difference in L_C between cores is due to the CT surrounding every core, where the smaller it is, the smaller the L_C for that core will be. Under the assumption that both cores in a fiber have the same L_B, which is reasonable since the cores are almost identical, we simulated the XT for L_B values within the previously mentioned range, calculated the corresponding L_C of each core, and observed where the measured XT intersects with the simulated one. The resulting L_C and L_B for each core and fiber are shown in Fig. 3(a). Additionally, in Fig. 3(b), we also plotted the relation between the measured D_{PMD} and CT of every core.



(a)



(b)

Fig. 3. (a) Relation between L_C and CT, and (b) between D_{PMD} and CT of every core in 2CF-A and 2CF-B.

We estimated an L_B of 40 mm for 2CF-A and 60 mm for 2CF-B. The L_C for core 1 is larger than core 2 in both fibers, which we assume is due to the increased resistance to structural perturbation provided by a larger CT. This is also observed in Fig. 3(b), where the D_{PMD} deteriorates when the CT is increased. These results seem to indicate that the larger the cladding diameter of a fiber is, the larger the CT of each core becomes in Hetero MCFs, which means a higher L_C. This in turn means that the XT can be improved at the cost of deteriorating the PMD by increasing the CT. It remains to be seen if this behavior also extends to other Hetero MCFs that have more than two cores, multiple types of cores, or different core arrangements within the cladding.

4. Conclusion

We investigated the relationship between IC-XT and D_{PMD} in Hetero MCF by using experimentally measured and simulated data from two Hetero MCFs with different cladding diameters. Results show that, based on the random polarization mode coupling in the cores, the IC-XT improves when either their L_B or L_C is increased, but at the cost of deteriorating the PMD. Additionally, we observed that an increase in the cladding diameter can lead to larger L_C values for every core in the fiber as a consequence of increased resistance to structural perturbations, which might be beneficial to the XT but detrimental to the PMD.

5. References

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