Stress Distribution Effects on Polarization-Mode Dispersion in Multi-Core Fibers

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Abstract: We investigate the origin of large PMD measurements in a 30-core heterogeneous MCF based on stress distribution analysis. We show proximity between cores and their refractive index profiles as main stressors, resulting in large PMD.

1. Introduction

Multi-core fibers (MCFs) have garnered considerable attention in the recent years as one of the most promising alternatives to achieving higher transmission rates than conventional single-mode fibers (SMFs) [1]. It is known that low polarization-mode dispersion (PMD) characteristics are desired to achieve such high transmission rates. In the case of MCFs, the PMD is heavily dependent on the birefringence characteristics of its cores. Although extensive research has already been done on the PMD and birefringence of SMFs, MCFs still have much to explore in these fields. Recent publications have reported that the parameters that characterize the stochastic nature of the birefringence in MCFs, namely the beat length L_B and the correlation length, can be in the order of magnitude of several centimeters [3], [4]. In contrast, the order of magnitude of these parameters in SMFs is known to be in the range of several meters to tens of meters [5]. Cores with such low values of L_B in MCFs can result in a deterioration of their PMD performance when compared to SMFs. Thus, it remains to be explored what could be the reason behind these small values of the birefringence L_B in MCFs and its impact on the PMD.

In this paper, we aim at providing an explanation behind these values by analyzing the stress distribution and its impact on the birefringence characteristics of a 30-core heterogeneous MCF (30c-HT-MCF) with four different core types, three of which have a low-index trench layer (LI-TL) profile. We numerically simulate the stress distribution between all cores of our fiber and investigate the correlation between the measured PMD and calculated L_B from the stress distribution. Our estimated values of L_B are in the range of several centimeters, well in agreement with the ones reported in [3], which would also explain the large PMD measurements of several cores in our MCF. We assume that a considerable part of the induced stress between cores is due to LI-TL profile of some of the cores and their close proximity.

2. Modeling of stress-induced birefringence in multi-core fibers

There are two main sources of birefringence in optical fibers: geometrical and stress-induced birefringence. Unless the fiber has cores with asymmetrical shapes, such as elliptical cores, geometrical birefringence can normally be neglected. The stress-induced birefringence refers to the stress that arises from doped silica glass with different thermal expansion coefficients, which generates stress when the glass is cooled down during the drawing process [6]. Then, due to the photoelastic effect, the refractive index (RI) of the glass changes in all directions. The stress distribution in the fiber and the changes in the RI will vary depending on the cladding and core material parameters, as well as the temperature change ΔT, defined as the difference between the operating temperature and the drawing temperature of the fiber. The material parameters of interest for the stress distribution analysis and calculation of the changes in the RI are the Young's modulus, Poisson's ratio, and the stress optical coefficients [6]. Once they are known, we can calculate the stressed RI in all directions of our MCF and then calculate the L_B of each core using the following expression:

$$L_B = \lambda / \left| n_x - n_y \right|, \tag{1}$$

where λ is the wavelength and n_x, n_y are the RI in the x, y directions, respectively. Here, we use COMSOL Multiphysics to simulate the stress distribution. This will allow us to evaluate the birefringence characteristics of each core in our MCF. For our analysis, we considered the materials parameters for the core, cladding, and LI-TLs presented in recent literature [7], which should serve as a good approximation for the purpose our research. As for the PMD measurements of our 30c-HT-MCF, we considered the PMD coefficient D_{PMD}, which is the measurement of the PMD of a core as a function of the square root of the length of the fiber. It is known that the PMD has an inverse relationship with the L_B [5], observation which is critical for our analysis.

3. Stress distribution analysis and PMD measurements

In order to see the stress distribution in an MCF that has cores with different RI profiles, we considered a 30c-HT-MCF with four different core types, three of which have a LI-TL and one has a step-index profile [8]. The cross-section view, core type allocation, and core profiles are shown in Fig. 1. The core parameters are listed in Table 1. The LI-TL relative refractive index Δ_T is –0.7%. The fiber has a cladding diameter of 229 μm, a length of 9.6 km, and the average core-to-core distance is 29.7 μm.

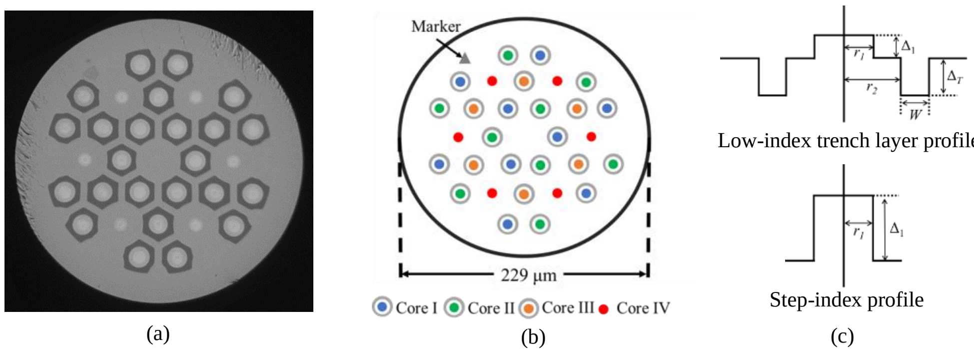

Fig. 1. (a) Cross-section view, (b) core type allocation, and (c) RI profiles of the 30c-HT-MCF with four different core types [8].

Table 1. Core parameters of the 30c-HT-MCF [8].

	r_1 (μm)	r_2/r_1	W/r_1	Δ_1 (%)
Core I	4.76	1.7	1	0.338
Core II	4.62	1.7	1	0.305
Core III	4.47	1.7	1.2	0.273
Core IV	4.68	-	-	0.388

Table 2. Material parameters of the 30c-HT-MCF [7].

Material Parameter	Core	Cladding	Trench
Thermal expansion coefficient (K^{-1})	7.9×10^{-7}	5.4×10^{-7}	1.01×10^{-7}
Young's modulus (Pa)	7.05×10^{10}	7.25×10^{10}	6.51×10^{10}
Poisson's ratio	0.183	0.186	0.149
First stress optical coefficient (Pa^{-1})		6.5×10^{-13}	
Second stress optical coefficient (Pa^{-1})		4.2×10^{-12}	
Temperature change ΔT (^{o}C)		–2000	

The material parameters for the core, cladding, and trench that were considered for the stress distribution analysis are listed in Table 2. For simplicity, we assigned the same material values to all four core types. The ΔT was set to –2000 °C taking into consideration the average temperature of furnaces used in the drawing process of optical fibers [9]. Lastly, a wavelength of 1550 nm was used for the simulation.

The stress and birefringence distribution plots of our MCF are shown in Fig. 2(a) and (b), respectively. The von Mises stress plot, namely Fig. 2(a), is useful in this case since it allows us to observe what areas in our fiber are subjected to more stress than others. The birefringence plot shows the magnitudes and directions of the birefringence in all cores of our MCF.

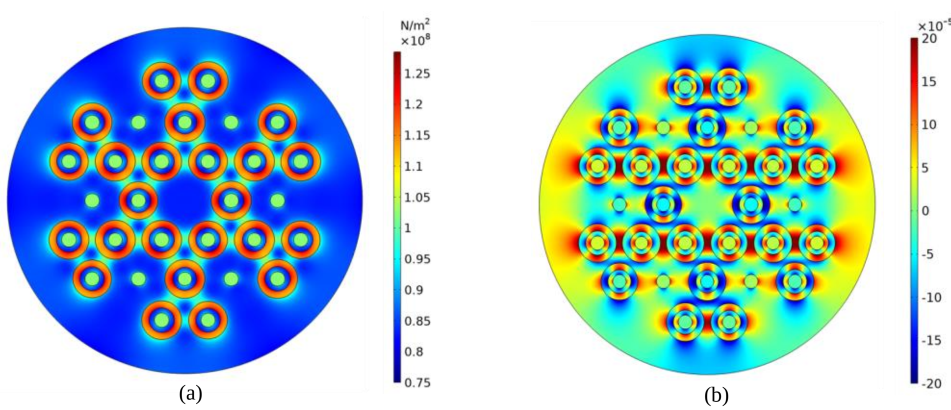

Fig. 2. (a) Von Mises stress and (b) birefringence distribution plots of our 30c-HT-MCF.

Our two main observations from the von Mises stress plot in Fig. 2(a) are that the LI-TLs are subjected to the most stress, likely due to having the lowest thermal expansion coefficient of all materials, and that there is some stress in the vicinity between cores with LI-TLs, as shown by the greenish stress between the cores. The cause behind the latter could be attributed to the close proximity between the LI-TLs of some of the cores. This would suggest that having cores too close to each other could result in a significant increase in the core birefringence, so special attention on the core-to-core distance should be considered in the design of this type of fibers. In the case of the birefringence plot in Fig. 2(b), we observed how some cores exhibit birefringence in the *x*-direction, while others show it in the *y*-direction. Depending on the application of the fiber, it might be desired to maintain the birefringence in the same direction on all cores, which should be considered in the design process. The magnitude of the birefringence in this case is somewhere between what is known in normal SMFs and polarization-maintaining fibers, which is to be expected since this fiber was not designed with goal of maintaining a given polarization state.

Next, from the stress distribution analysis we were also able to calculate the respective values of L_B for all cores of our MCF using Eq. (1). The estimated values are shown on top of their respective cores in Fig. 3. We observe that the order of magnitude of the L_B of all cores ranges from several centimeters to several tens of centimeters, depending on its positioning in the fiber. Similar to a recent report [3], the order of magnitude of the L_B from the cores of our MCF is several orders of magnitude smaller than those of SMFs. We assume this is due to the induced-stress from the LI-TLs of neighboring cores and their close proximity to each other, causing the birefringence to increase.

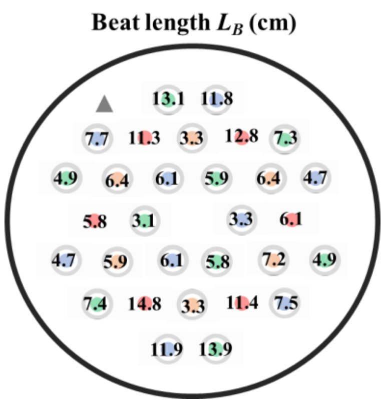

Fig. 3. Estimated values of L_B for all cores of our 30c-HT-MCF.

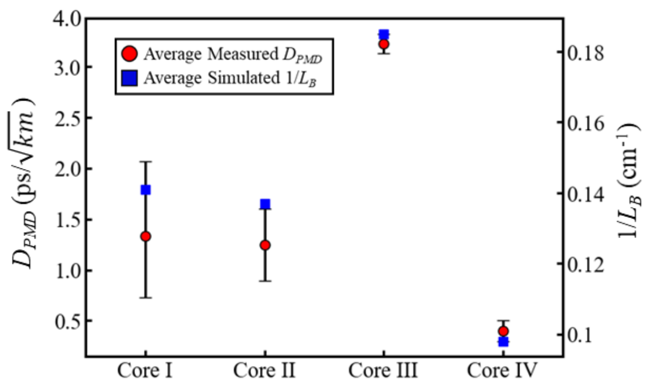

Fig. 4. Error bar plot of D_{PMD} measurements (left axis) and average simulated $1/L_B$ (right axis) for each core type of our 30c-HT-MCF.

Finally, we also experimentally measured the PMD in the 30c-HT-MCF. The D_{PMD} measurements and average simulated $1/L_B$ per core type of our MCF are summarized in the plot shown in Fig. 4. We observed that core types I and II have similar PMD measurements, which could be explained by their similar values of L_B. Core III has the largest PMD of all core types, which might be due to having the lowest average L_B of all core types. On the other hand, Core IV has the lowest PMD of all, which we assume is due to having the largest average estimated L_B. Overall, the difference in order of magnitude on the PMD between our MCF and those of SMFs could be attributed to the increased core birefringence product of the stress originating from neighboring cores, as observed from our stress distribution analysis and L_B estimations.

4. Conclusions

We performed a stress distribution analysis on a 30c-HT-MCF with four different core types to evaluate the impact of stress-induced birefringence on the PMD in MCFs. The analysis consisted of numerically simulating the stress between cores of our MCF and calculating their respective L_B. Our findings show that a large part of the induced-stress on the cores of our fiber stems from the LI-TL of neighboring cores and their close proximity to each other. Additionally, the order of magnitude of the L_B of our cores ranged from several centimeters to several tens of centimeters, which could explain the large PMD measurements of our MCF when compared to those of SMFs.

5. References

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