学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

A Study on Random Polarization-Mode Coupling Effects and Stress Distribution Characteristics in Heterogeneous Multi-Core Fibers

（異種マルチコアファイバにおけるランダム偏波モード結合効果と応力分布特性に関する研究）

The rapid expansion of global data traffic driven by cloud services, high definition video, connected devices, immersive technologies such as virtual reality, and the growing use of artificial intelligence has pushed current optical networks close to their fundamental capacity limits. To address this growing pressure, researchers are turning to space-division multiplexing, which increases transmission capacity by using multiple spatial channels within a single fiber. Among these technologies, multi-core fibers (MCFs), which integrate several independent cores into one cladding, have emerged as a leading approach because they can be deployed alongside existing optical infrastructure with minimal changes to current network architectures.

Despite their advantages, MCFs face two impairments that can degrade signal quality: inter-core crosstalk (IC-XT) and polarization-mode dispersion (PMD). While the former generally has a stronger impact, both must be carefully managed. Inter-core crosstalk occurs when light unintentionally couples from one core to another, especially when cores are placed close together. Heterogeneous (HT) MCFs, where each core is slightly different, can mitigate this coupling, although their performance is strongly dependent on geometric parameters such as core spacing and refractive-index profiles. Polarization-mode dispersion arises when the two polarization components of light travel at different speeds. In MCFs, this effect is strongly influenced by the complex stress patterns created by multiple cores inside a single cladding. Both impairments can vary significantly across different fiber designs, and several experimental observations remain unexplained—such as the dependence of crosstalk on cladding diameter and the wide variation of PMD reported in the literature.

This dissertation proposes that birefringence—the property that causes polarization components to propagate at different velocities—provides a unifying explanation for these behaviors. The work examines how MCF design choices shape the internal stress distribution, how this stress leads to birefringence, and how birefringence ultimately affects both IC-XT and PMD. The research has three main goals: (1) to clarify how inter-core IC-XT and PMD depend on cladding diameter in heterogeneous MCFs through combined numerical and experimental studies; (2) to establish a numerical framework for calculating birefringence in MCFs and relating it to stress and PMD; and (3) to explore stress-engineering techniques using stress-applying rods to suppress birefringence in high-core-density MCFs. Together, these contributions provide new physical insights and design guidelines for the next generation of high-capacity MCFs.

This dissertation is structured as follows:

In chapter 2, we detail the theoretical framework for characterizing random polarization-mode coupling (RPMC) effects in MCFs, its incorporation into the coupled-mode equation for numerical evaluation of the IC-XT, and its relation to PMD. This framework establishes the basis for assessing the dependence of IC-XT and PMD on the cladding diameter.

In chapter 3, we present an analysis of how RPMC effects can account for the observed dependence of IC-XT and PMD on the cladding diameter in two 2-core weakly-coupled HT-MCFs with identical core types but different cladding diameters. By combining numerical simulations with experimental measurements, birefringence parameters were estimated, revealing that differences in these parameters may explain the observed cladding diameter dependence.

In chapter 4, we investigate the relationship between PMD and stress-induced birefringence through a numerical stress distribution analysis of selected MCF designs reported in the literature. Focusing on residual thermal stresses as a baseline, this study provides insight into how birefringence characteristics contribute to variations in PMD and offers guidance for future MCF design.

In chapter 5, we propose and demonstrate a method to reduce core birefringence in trench-assisted HT-MCFs by engineering stress fields through the incorporation of stress rods. Two structures—a 4-core and an 8-core design with standard cladding diameter—are numerically optimized in terms of rod count, placement, and material composition. The results show that SMF-like birefringence can be achieved across all cores, highlighting the adaptability of the method to different doping materials.

Lastly, in chapter 6, we conclude the dissertation by summarizing the key findings and contributions of this study.