称号及び氏名	博士（工学）　中村　篤志
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論　　文　　名	「A Study on Optical Fiber Testing Technique Based on Backscattered Power of Higher-Order Mode（高次モードの後方散乱光を利用した光ファイバ試験技術に関する研究）」
論文審査委員	主査　大橋　正治
	副査　山田　誠
	副査　小西　啓治
	副査　久保田　寛和

論文要旨

Along with the recent developments in the Internet, the role of information and communication technology (ICT) has transformed from a mere communications tool to a multimedia communications tool. ICT is now being utilized in various services such as online electronic transactions, disaster prevention, education, etc., and has become essential for society. As a result, fiber-optic communication systems that best support the ICT are increasing in importance, and any fault in a system will seriously impact society.

Unfortunately, some optical fibers exposed to severe environments for a long time are currently deteriorating. In particular, macrobending and microbending losses are increasing. Although this deterioration may initially have no impact on system performance, it will gradually grow worse and eventually cause system outages. To maintain reliable transmission systems, such a temporal deterioration of optical fibers must be detected before system outages occur so fiber cables can be replaced as needed.

However, it is sometimes difficult to ensure enough time for cable replacement, since considerable time is required for replacing field-installed optical fiber cables. This problem is most serious in the replacement of trunk cables, as more than one year is often needed from planning to completion. In addition, NTT Group is facing a decline in maintenance workforce. The number of maintenance workers is expected to decrease by about 40% in the next ten years, with further declines after that. Since more can be expected to deteriorate while the maintenance labor force is declining, maintaining the reliability of optical fiber networks will problematic with the current maintenance approach.

To overcome these difficulties, investing time and energy in maintenance works more efficiently than is possible at present is essential. Concretely speaking, the current state of deterioration and its minor temporal changes must be first understood, and then long-term strategic maintenances that take account of the degree of deterioration and the impact of the service outage on society must be developed. Consequently, establishing an optical fiber testing technology that can detect the progressive deterioration

of optical fibers earlier than existing test technologies is an urgent goal that must be addressed.

This thesis contributes toward the progress of optical fiber testing technologies that can help to prevent the outages of fiber-optic transmission systems. The main objective of this thesis is to develop a novel optical fiber testing technique that can detect macro/micro-bending with higher sensitivity than that offered by conventional optical time domain reflectometry (OTDR), which is a technique widely used for testing optical fibers. To achieve this goal, this thesis utilizes the second-order (LP11) mode as it offers higher sensitivity to macro/micro-bending than the fundamental (LP01) mode that is used for signal transmission and conventional optical fiber testing. By measuring the optical losses of the LP11mode occurring in optical fibers, it can be expected to detect macro/micro-bending with high-sensitivity than conventional OTDR. Thus, a novel backscattering technique that can measure the optical losses of the LP11mode is studied so as to detect macro/micro-bending that cannot be found with conventional OTDR.

This thesis consists of seven chapters and each is summarized below.

Chapter 1 is an introduction, and provides the background, objectives, and outline of this thesis.

Chapter 2 starts with a brief description of the fundamentals of OTDR. Then, it proposes a novel backscattering technique that employs not only the LP01mode, which is generally used for signal transmission and optical fiber testing, but also the LP11mode, which is more sensitive to changes in the macro/micro-bending states of fibers under test (FUTs). Unlike conventional OTDR, the proposed technique generates the LP11mode component of the backscattered light as well as the LP01mode component by injecting a short light pulse (probe pulse) with wavelength below the cut-off wavelength of FUTs, and observes each mode component individually by employing a mode selective coupler (MSC). To clarify the basic principles of the proposed technique, how each mode couples to other modes through Rayleigh scattering is theoretically investigated and each mode component of the backscattered power is modeled mathematically.

Chapter 3 introduces a highly sensitive technique that can detect macrobending. First, macrobending losses of widely used SMFs are investigated theoretically, and then a technique for detecting macrobending with high sensitivity is proposed based on the novel backscattering technique. To confirm its feasibility, macrobending losses with various bend radii are measured using the proposed technique; comparisons are made with conventional OTDR operating at the wavelength of 1.65 μm. It is clarified that the proposed technique is promising for detecting macrobending more sensitively than conventional OTDR.

Chapter 4 describes a diagnostic technique for differentiating macrobending from fusion splicing based on the novel backscattering technique. First, macrobending and fusion splicing losses obtained with the novel backscattering technique are investigated theoretically. Then, the loss ratios yielded by the LP01and LP11mode components of the backscattered light are used to propose a technique for identifying whether the loss-inducing factor is macrobending or fusion splicing. Moreover, to verify the proof-of-concept, macrobending losses with various bend radii and fusion splicing losses with various core axis misalignments are measured. It is clarified that macrobending and fusion splicing losses can be distinguished by evaluating the loss ratio of the LP01to LP11mode components of the backscattered light.

Chapter 5 describes a highly sensitive detection technique of microbending. First, microbending losses of widely used SMFs are investigated theoretically, and then a technique for detecting microbending with high sensitivity is proposed based on the novel backscattering technique. Next, to demonstrate its feasibility, the microbending losses generated by winding an optical fiber around a sandpaper-wrapped drum with various winding tensions are measured, and comparisons are made with conventional OTDR operating at the wavelength of 1.65 μm. It is confirmed that the proposed technique can detect microbending with higher sensitivity than conventional OTDR. Finally, the microbending loss increase generated when the optical fiber is exposed to high temperature and humidity is observed. It is demonstrated that the proposed technique can detect microbending loss increases at an early stage. It is clarified that the proposed technique is useful for detecting progressive microbending much sooner than conventional OTDR.

Chapter 6 describes the problem of amplitude fluctuation in the backscattered waveforms generated by the novel backscattering technique and a reduction solution. First, the backscattering amplitude coefficients of the higher-order vector modes generated from the LP01mode traversing the FUT (the probe pulse) is analyzed, and then how the states of polarization (SOP) of the higher-order vector modes evolve through the backscattering process is theoretically investigated. The investigation yields the technique of scrambling the SOP of the probe LP01mode; it significantly reduces the amplitude fluctuation. To confirm the effectiveness of the proposed technique, experiments are undertaken under the following conditions: a) without using the proposed technique, and b) with the proposed technique. It is clarified that the proposed technique is effective in reducing the modal birefringent fluctuations in the LP11mode component of the backscattered light.

Chapter 7 summarizes the results obtained in this study.

This study can be expected to contribute to maintaining the reliability of optical fiber networks by establishing the key optical fiber testing technologies that can detect macro/micro-bending with higher sensitivity than conventional OTDR.

審査結果の要旨

本論文は、光ファイバの製造時の高品質性の担保、ケーブル化・敷設工程での品質変化、さらに長期使用後の劣化状況を把握し、計画的な保守運用を行うために必要な光ファイバ試験技術として、光ファイバを伝搬する高次モードの後方散乱光を利用した、高感度な光ファイバ試験技術について研究したもので、以下に示すような成果が得られている。

(1) 光ファイバの品質を低下させる要因の一つである曲げの検出への適用について検討し、既存の OTDR では把握することができなかった曲げを、LP_{11} モードの後方散乱光成分を測定・解析することで検出可能であることを明らかにした。

(2) 光ファイバの曲げによって生じる損失は通常反射を伴わないため、OTDR 波形から融着接続による損失と区別することは難しい。そこで、後方散乱光の LP_{01} モード成分と LP_{11} モード成分に生じる損失の比を評価することで、曲げ損失と融着接続損失を識別する手法を提案し、実験的に検証を行い、その有効性を明らかにした。

(3) マイクロベンドよって生じる損失は、通常長距離にわたって発生するため、その損失が局所的に小さい場合においても、通信システム全体には大きな影響を及ぼすことがある。しかしながら、マイクロベンドにより生じる光ファイバのケーブル化工程や敷設工程，敷設後の経年劣化を詳細に把握することは難しい。そこで、後方散乱光の LP_{11} モード成分を測定・解析することで、既存の OTDR よりも高感度にマイクロベンドを検出可能であることを明らかにした。さらに、これまで把握することができなかったマイクロベンドの詳細な状態把握や、既設光ファイバの経年劣化によるマイクロベンド損失増加の早期発見への適用性を明らかにした。

(4) 後方散乱光の LP_{01} モード成分と LP_{11} モード成分を個別に測定する OTDR では、LP_{11} モード成分から得られる測定波形に長手方向での LP_{11} モードの強度分布変動に起因した振幅揺らぎが生じる問題がある。この振幅揺らぎは LP モードを分離する OTDR に特有の問題であり、モード複屈折性揺らぎによるものである。このモード複屈折性揺らぎの原因となる

後方散乱光の LP_{11} モード成分の強度分布変動を定式化するとともに、その低減法を提案し、その有効性を明らかにした。

以上の研究成果は、光ファイバに与えられた外乱によって経時的に変化する伝送特性を高感度に検知する試験法を開発しており、本試験法は、製造工程の光ファイバから実際に敷設された光ファイバ通信線路までの、いわゆる光ファイバ伝送路の健康診断を行う試験法として多いに貢献できる技術として期待できる。また、申請者が自立して研究活動を行うのに必要な能力と学識を有することを証したものである。学位論文審査委員会は、本論文の審査ならびに学力確認試験の結果から、博士(工学)の学位を授与することを適当と認める。