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論　　文　　名	「A Study on Innovative Optical Fibers for Large Capacity Transmission Systems」 （大容量伝送システムのための革新的光ファイバに関する研究）
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論文要旨

With the advantages of low attenuation, broad bandwidth, lightweight, and very small size, optical fiber had been considered to be deployed in telecommunication network since Corning Glass Works demonstrated 20dB/km optical fiber in 1970 following Nishizawa’s idea regarding optical waveguide and Kao’s prediction.

At the initial stage of deployment, the cost of an optical fiber was very expensive and manufacturing and splicing technologies were immature. Therefore, a multimode optical fiber, which has a larger core diameter and easy to splice, was selected even though it has bandwidth limitation due to modal dispersion compared with a single-mode optical fiber. Then, progress of manufacturing and splicing technologies made it possible to introduce single-mode optical fibers (SMFs) to the long-haul network.

On the other hand, deployment of optical fiber cables to access network was not easy because cost of optical fiber transmission system was very expensive compared with metallic ones. Energetic research and development for fiber to the home (FTTH) was started in NTT laboratories. The cost of FTTH was dropped sharply and became the same level as metallic cable systems in 2000.

In early 2000's single-mode fibers were introduced to all over the telecommunication networks from backbone to access networks. Maximum transmission speed was expected to be more than 40 Gb/s, and with a wavelength division multiplexing (WDM) technology, total capacity of one fiber was expected to exceed 10 Tb/s.

Many kinds of optical fibers have been developed and deployed in the telecommunication network to satisfy system requirements for the transmission capacity, wavelength region, bending characteristics and reliability. The traffic of backbone network has been increasing rapidly corresponding to the growth of broadband users in Japan. The capacity of a fiber in backbone network was 1.6 Gb/s in 1987 and has increased to 1.6 Tb/s in 2007.

On the other hand, as the information capacity increases by about 40 % per year in Japan, a fiber which can carry the capacity of Pb/s will be needed in 2027.

Recent study showed the conventional single-mode fiber, most popularly used in telecommunication network, was approaching the capacity limit imposed by the combination of Shannon's information theory and nonlinear fiber effect. Therefore, an innovative optical fiber to overcome the capacity limit of the conventional single-mode fiber should be developed for future ultra large capacity transmission systems that can accommodate the traffic growth in telecommunication network.

According to Shannon-Hartley theorem, maximum channel capacity is proportional to signal to noise ratio (SNR) and bandwidth of the channel. There are two ways to increase SNR by transmission media. One is to reduce the loss and the other is to enlarge maximum input power of transmission media. For an optical fiber, the former means the low transmission loss and the latter means the large effective area for reducing nonlinear effect and fiber fuse. Low transmission loss will realize a transmission system with a long transmission distance. Enlarged bandwidth in optical transmission system means to extend the operating wavelength range. To fulfill these in optical fiber, not only low loss in the wide wavelength range but also dispersion characteristics should be controlled to reduce deterioration of signal due to delay and nonlinear effect. In addition to these characteristics, it is learned in deployment history that low bending loss characteristics is indispensable for a practical deployment.

In those transmission characteristics, PCFs are very attractive transmission media since PCFs can provide the unique dispersions and the wavelength dependence of mode field diameter (MFD) that are not obtainable in the conventional single-mode fibers. The intrinsic loss is estimated to be less than that of the conventional SMF and bending loss characteristics are superior to those of the conventional SMF. During the research and development of novel PCFs, an immediate application is found for the indoor wiring of FTTH. Because of ultra-low bending loss characteristics, PCF is suitable to the optical fiber wiring used in the circumstance with many bend and possibly handled like a metallic wire with small bending radius by technicians and customers.

Another alternative is to use multimode optical fiber because it has much large effective area compared with the SMFs and mode division multiplexing will add another dimension to enlarge the capacity of transmission system. In the deployment history, the multimode fiber (MMF) was given up because of large modal dispersion and modal noise problem. However, the development of the digital signal processing (DSP) technology makes it possible to utilize a few number of multi-input multi-output (MIMO) processing in the transmission systems using the MMFs or few mode fibers (FMFs). Therefore, a few-mode optical fiber that has a low differential modal group delay (DMD), a large effective area and a low bending loss are focused on.

The main objective of this thesis is to develop innovative optical fibers for future ultra large capacity transmission systems that overcome the capacity limit of conventional SMF and can accommodate the rapid traffic growth in telecommunication network. As the main technical challenges of the novel optical fiber, an innovative optical fiber with a low transmission loss, a large effective area, a flexible chromatic dispersion and low bending loss characteristics is realized.

Chapter 2 proposed the photonic crystal fibers (PCFs) as the novel optical fibers that overcome the tradeoff of large effective area and cutoff wavelength or bending loss of conventional SMF utilizing refractive index difference between core and cladding for confinement of light. A low loss PCF design for reducing confinement loss and fabrication technology for long length PCF were proposed. The PCF with a loss of 0.37 dB/km at 1.55μm and fiber length of 10km has been realized. The possibility of optical loss reduction of PCF has been also shown by reducing the OH absorption. A dense wavelength division multiplexing transmission experiment has been also demonstrated using the fabricated PCF.

Chapter 3 proposed a hole-assisted PCF (HAPCF) with good bending performance for optical wiring because optical fiber is installed with many bend and possibly handled like a metallic wire with small bending radius by technicians and customers. The optimal design of HAPCF has been clarified and it has been confirmed that only a negligible loss increase with a bending radius of 10 mm. It has been also shown that the long-term reliability of HAPCF can be improved using an appropriate pre-process. Moreover, it has been also clarified that connection losses using both conventional fusion splice and mechanical splice methods to HAPCF were no more than 0.5 dB.

Chapter 4 proposed an optimized graded-index two mode fiber (GI-TMF) that has a low DMD, low bending loss and large effective area A_{eff}. It has been clarified the suitable fiber parameters for the GI-TMF satisfying requirements that are DMD = 0 ps/km, A_{eff} of more than 150 μm^2 and bending loss for LP_{11} mode of less than 0.01 dB/km at R = 40 mm and 1550 nm. It has been shown experimentally that the fabricated GI-TMF had a A_{eff} of 150 μm^2 for LP_{01} mode, and approximately 0.016 dB/km bending loss for LP_{11} mode at R = 40 mm and 1550 nm. The mode coupling at the splice point of TMF has been estimated by using finite element-beam propagation method. It has been clarified that mode coupling noise of more than -20 dB at the splice point may be generated when offset value is within 1 μm. It has also been clarified that the present GI-TMF is suitable for mode division multiplexing and has a potential to reduce complexity of the digital signal processor systems for the MIMO processing.

This study clarified that the innovative optical fibers for overcoming the capacity crunch of the conventional SMFs will be able to contribute to realize the ultra large capacity transmission systems to accommodate dramatically increasing traffic.

審査結果の要旨

本論文では、既存のシングルモード光ファイバの伝送限界を打破するための革新的な光ファイバとしてフォトニッククリスタルファイバ（PCF）およびヒューモードファイバ（FMF）を提案しており、それらのファイバの伝送特性について明らかにしている。本論文で得られた主な結果は、以下の項目に要約できる。

(1)　単一モード領域および曲げ損失特性を向上するために、フォトニッククリスタルファイバ（PCF）を提案している。PCF の伝送損失を低減と長尺なファイバの実現をめざした波長帯域拡大用のファイバが検討されており、1.55μm で 0.37dB／km の損失を持つファイバ長 10km の PCF が実現されている。特に、PCF の損失低減のために、OH 吸収損失低減技術を明らかにしている。さらに、本 PCF を用いた波長多重システムへの適用実験を行い波長帯域の拡大に反映できることを明確にしている。

(2)　アクセス系の配線用光ファイバで施工やハンドリングによって損失が増加しないファイバが望まれており、これを改善するために曲げ特性を良好とする PCF（HAPCF）の適用を提案している。HAPCF の適切な構造パラメータが選択され試作された。試作された HAPCF は 10 mm の曲げ半径において損失がほとんど観測されず、十分な信頼性を有することおよび融着接続およびメカニカル接続特性について良好であることが示されており、本ファイバが実用に十分供することが明らかにされている。

(3)　実効断面積拡大ファイバとして、FMF が提案されている。このファイバを用いたモード多重伝送システムを実現するためのファイバ設計法を明確にしている。モード群遅延時間が小さく、低曲げ損失、および大きい実効断面積等の適切な要求条件を有するグレーデッド型２モードファイバ（GI-TMF）を提案している。設計結果に基づいて TMF を試作しその伝送特性を評価している。評価結果より、各種特性が要求条件を満足していることが示され、本設計ファイバがモード多重伝送システムに適用できることを明確にしている。

以上の研究成果は、既存光ファイバの伝送容量の限界を打破するための光ファイバに関する重要な知見を与えるとともに、本分野の学術的・産業的な発展に貢献するところ大である。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最終試験の結果から、博士（工学）の学位を授与することを適当と認める。