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A Study on Innovative Optical Fibers for Large Capacity Transmission Systems

Kiminori Sato

January 2015

Doctorial Thesis at Osaka Prefecture University
A Study on Innovative Optical Fibers for Large Capacity Transmission Systems

This research was made in Nippon Telegraph and Telephone Corporation and Fujikura Ltd., and submitted for the doctoral thesis of Osaka Prefecture University

Kiminori Sato
January 2015
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Chapter 1

Introduction

1.1 Background

With the advantages of low attenuation, broad bandwidth, light weight, and very small size, optical fiber had been considered to be deployed in telecommunication network since Corning Glass Works demonstrated a 20dB/km optical fiber in 1970 [1] following Nishizawa’s idea regarding optical waveguide and Kao’s prediction [2]. In late 1970's, Nippon Telegraph Telephone Public Corporation (NTT) considered to deploy optical fiber cables to trunk network, which was expanded rapidly to accommodate growing telephone traffic, because repeater spacing of optical fiber transmission system will be much longer than that of coaxial and metallic cables.

At the initial stage of deployment of optical fiber transmission system, 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. In 1981, first commercial introduction of graded-index (GI) multimode optical fiber cables started. Then, progress of manufacturing and splicing technologies made it possible to introduce single-mode optical fibers (SMFs) to the long-haul network. SMFs were considered as the main transmission media for backbone network instead of coaxial and metallic wire.

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 that of metallic one. First introduction of optical transmission system to access network was the dedicated line for video transmission. In 1980's, NTT seriously considered about fiber to the home (FTTH) for the next stage of access network infrastructure towards multimedia era. NTT started information network system (INS) Model System Trial including real FTTH at Mitaka area, suburbs of Tokyo in 1984. NTT announced VI&P (Visual, Intelligent and Personal) concept in 1990 and energetic research and development for FTTH was started in NTT laboratories. The cost of FTTH was dropped sharply and became the same level as metallic cable systems in 2000. First commercial FTTH service started in 2001 at the maximum speed of 10Mb/s with single-mode optical fiber cables.

In early 2000's single-mode fibers were introduced all over the telecommunication networks from backbone to access networks. Maximum transmission speed was expected to be more than 40Gb/s, and with a wavelength division multiplexing (WDM) technology, total capacity of one fiber was expected to exceed 10Tb/s. Many people believed there will be no need for another transmission media.

However, the progress of video and computer technology, and diffusion of high-speed internet will cause dramatically increase of telecommunication traffic and the volume of traffic will reach a
practical limit of single-mode optical fiber within two decades [3]. If new transmission media are necessary from our experience, it may take more than 10 years from the start of research to massive deployment. Therefore, the research for innovative optical fibers have started for the ultra large capacity transmission systems, which will overcome the capacity limit of conventional single-mode fibers.

In this chapter, conventional optical fibers deployed in telecommunication network and their limitations of transmission capacity are discussed through the deployment history of optical fibers in Japan. Then, a structure of this thesis and the study items which are described in chapters 2-4 that aim at breaking the fundamental capacity limit of conventional single-mode optical fibers are briefly summarized.
1.2 Deployment History of Optical Fibers for Telecommunication Networks

1.2.1 Long-haul Network

NTT has been developing optical fiber transmission systems for the implementation of the comprehensive telecommunications network since early 1970's. At that time, manufacturing technology of optical fiber was poor and it was difficult to fabricate single-mode optical fibers which have a smaller core diameter than multimode optical fibers. It was also difficult to connect single-mode optical fibers with a low splice loss. Therefore, in the first generation multimode optical fibers were focused on.

In 1981, a 32 Mb/s transmission system (F-32M system: 480 telephone circuits) using a graded-index (GI) multimode optical fiber cable was introduced into the medium capacity intra-city transmission lines. This system was the first optical fiber cable system implemented by NTT. In this system, the operating wavelength was 0.85 µm and the maximum repeater spacing was 10km. Since then, GI optical fiber cables have also been used for F-100M and F-6M systems (which correspond to 1,440 and 96 telephone circuits, respectively) and the operating wavelength was shifted to 1.3 µm, where the attenuation of optical fiber is smaller than that of 0.85 µm and maximum repeater spacing reached to 15km.

Transmission characteristics of the multimode optical fiber were greatly influenced by a mode coupling between each propagation modes. Discontinuities of multimode optical fibers such as connecting and bending points, core deformation along the longitudinal direction will
cause the mode coupling. The mode coupling is also influenced by excitation conditions of light source. In the commercial test of GI multimode optical fiber cables, the mode coupling coefficient in the deployed optical fiber cables were measured. Such results were reflected to the economical bandwidth specifications of GI optical fiber cables.

As the coherence of light source and multimode optical fiber cables improved, the mode coupling in multimode optical fiber cables caused more fluctuation of output power in the transmission system. This phenomenon is called modal noise and multimode optical fibers for higher bit rate and longer length transmission system in telecommunication networks was faced difficulties at that time.

Therefore, a single-mode optical fiber cable with superior transmission characteristics such as low optical loss and broad bandwidth and free from modal noise has been introduced with the progress of manufacturing and splicing technologies of optical fibers. Commercial introduction of SMFs was started in 1983 as the Japan transverse optical fiber cable transmission route, connecting from Asahikawa to Kagoshima and accomplished in 1985. This cable has been applied to long-haul large-capacity transmission lines all over Japan along with an F-400M (5,760 telephone circuits) transmission system and maximum repeater spacing of 40km [4]. Then, the system was upgraded to F-1.6G (23,040 telephone circuits) and that capacity was enough to carry telephone traffic and replace existing coaxial transmission system with maximum capacity of 10,800 telephone circuits (C-60M transmission system). However, NTT were annoyed by the short time transmission system down under cable transfer work. Because technicians unconsciously bend the fiber with a small bending radius at the splicing points and this causes a huge macro bending loss that is over the loss budget of the transmission system.

Then late 1980's, transmission systems at the 1.55 μm
wavelength where attenuation of optical fiber is lowest in silica based optical fiber were noted because many optical fiber submarine cable systems were scheduled to deploy all over the world and longer repeater spacing was required. However, conventional single-mode fibers were inappropriate for the 1.55 µm wavelength optical transmission systems at that time because the chromatic dispersion and the macro bending loss are large at the 1.55 µm wavelength region.

As mentioned above it moved to the research and development of 1.55 µm wavelength optical transmission system that can expand the transmission distance by applying the SM fiber to 1.55 µm wavelength region where the optical loss is minimum.

Dispersion-shift fibers (DSFs), which have low chromatic dispersions and low losses in the 1.55 µm wavelength region, were developed at the same time for the same purpose. In 1984, the segmented core DSF [5] whose index profile has a ring outside a core was proposed by Corning. Segmented core DSF has the larger MFD and the lower bending loss by utilizing the mode coupling between a core and a ring.

In 1986, NTT proposed a new DSF with a dual shape core (DSC: Dual Shape Core) [6] which is in no way inferior to the segmented core DSF. DSC-DSF has the large MFD, low macro-bending loss and the good dispersion controllability.

Figure 1-1 shows the typical index profile, optical loss and chromatic dispersion characteristics of the developed dispersion shifted optical fiber. These optical fiber cables were introduced into the almost all backbone network of NTT with Synchronous Digital Hierarchy (SDH) optical transmission system up to 2.5 Gb/s and realized maximum repeater spacing of 80 km and 120 km at terrestrial and submarine section, respectively [7].
In 1990's, due to an invention of optical fiber amplifiers [8], the research and development of wavelength division multiplexing (WDM) technologies as well as dispersion compensating fibers (DCF) have been advanced. Capacity of optical fiber transmission system has dramatically increased with utilizing those WDM technologies. At present, the maximum transmission speed of single channel wavelength reached 40 Gb/s and 10 Gb/s x 80 wavelengths transmission system with conventional dispersion shifted fibers has already introduced in the backbone network for a practical use.

![Figure 1-1](image-url)
1.2.2 Access Network

The configuration of an access network is shown in Fig. 1-2. The access network consists of four facilities, namely central office facilities, feeder section facilities, distribution section facilities and user section facilities from a central office to residential premises. It is the most important that economical and efficient feeder and distribution section facilities for fiber-to-the-home (FTTH) will be constructed. To achieve this, less expensive and easily installed optical fiber cable technologies for the feeder and distribution sections must be developed. Termination cables terminate fibers at a fiber termination module (FTM) [9] or an integrated distribution module (IDM) [10] placed in a central office, and feeder cables are installed in a cable tunnel or a duct located between the FTM or IDM in a central office and the distribution point (feeder point) in the feeder section. Distribution cables, which are mainly installed between telecommunication poles, are connected to the feeder and distributed cables between feeder points and access points close to residential premises. Therefore, aerial self-supporting type optical fiber cables that can be easily installed are needed.

Figure 1-2 Access network configuration
In 1982, subscriber optical fiber cable was firstly introduced to small-scale leased lines for video transmission services. NTT used subscriber optical fiber cables, which contain maximum 100 GI optical fibers, for 4 MHz video and digital transmission services up to 6.3 Mb/s, since the transmission characteristics required for these services were obtained at lower costs than those of single-mode optical fiber cables, and easier fiber splicing can reduce the construction costs. In the application to broadband leased lines, the cable technology resembled that for trunk networks.

However, a new comprehensive telecommunications network serving widespread subscribers (first implemented as INS Model System in 1984) has led to the development of cable technology suitable for the subscriber area. As a result, NTT has developed a high density subscriber optical fiber cable with a five-fiber ribbon structure and slotted rod, as well as related techniques such as mass-fusion splice and multi-fiber optical connectors. Maximum fiber count was 200 and increased to 600 in 1987 [11]. At this stage, for broadband services and digital transmission services with a transmission speed of higher than 384 kb/s, optical fiber transmission systems were used since they are cost-effective and free from cross-talk problems.

As the deployment of single-mode optical fiber cables in the trunk network increased all over the world, the cost of single-mode optical fiber dropped sharply. At the same time, splice loss of multi-fiber fusion splice and connectors for single-mode optical fibers decreased because the core concentricity error and cladding diameter difference became small by the improvement of manufacturing technologies. In 1988, NTT introduced single-mode optical fiber to an access network and unify a ribbon structure with 4 fibers for the trunk network.

In 1990, NTT announced VI&P (Visual, Intelligent & Personal) Concept and clearly mentioned to deploy FTTH all over Japan until
2015. To realize this target, cost reduction of FTTH deployment was the most critical issue for NTT because it was more than seven times higher than the metallic ones. Therefore, NTT laboratories have started energetic research and development of FTTH technologies to reduce cost of FTTH to the same level of metallic cable systems in 2000. As the research and development made progress, the deployment cost of FTTH decreased drastically and the target was achieved. First commercial FTTH service started in 2001 at the maximum speed of 10Mb/s utilizing single-mode optical fiber cables. Since then, number of FTTH subscriber has grown rapidly in Japan and now it has reached more than 20 millions. Transmission speed was also enlarged to maximum 100Mb/s and 1 Gb/s.

After starting massive deployment of FTTH, NTT were annoyed by handling problem of optical fibers that also happened in long haul network. Especially in house wiring, there are a lot of bending points and customers didn't understand the difference between optical fiber and metallic cords. Technicians and customers often bent optical fiber in a small radius that cause big attenuation increase and in the worst case fiber breaks.

Therefore, a new optical fiber that has a smaller minimum bending radius with a smaller loss increase and sufficient reliability at a smaller minimum bending radius have to be developed. The photonic crystal fiber (PCF) including a hole assisted type PCF (HAPCF) is focused on because of very low bending loss compared to conventional optical fibers [12]. The HAPCF that has a negligible loss increase at a minimum bending radius of 10 mm and a long-term reliability has been developed. Moreover, this fiber can use conventional connection technology and reasonable attenuation can be obtained when connecting with conventional fibers.
1.3 Technical Issues of Transmission Media for the Future Networks

Many kinds of optical fibers have been developed and deployed in telecommunication network to satisfy system requirements for 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.

However, 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-Hartley theorem and nonlinear fiber effect [13]. Therefore, an innovative optical fiber to overcome the capacity limit of 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 are indispensable for a practical deployment.

Figure 1-3 summarizes the technical issues for innovative optical fibers. The relationship between requirements from transmission system and required transmission characteristics of optical fibers will be clarified.

![Figure 1-3 Technical issues for optical fibers](image)

In a conventional single-mode fiber that has a simple refractive index profile between core and cladding, the relationship between the large effective area and the cutoff wavelength or bending loss shows a tradeoff. Therefore, to enlarge the effective area while keeping single-mode transmission and low bending loss characteristics, the new refractive index profile for confining the light in the core of the optical
fiber is necessary. Realization of low transmission loss and flexible chromatic dispersion characteristics are another challenging issues for the new type single-mode optical fiber.

To get large effective area with a conventional method to confining the light in the core of the optical fiber, multimode operation at least in the operating wavelength should be considered. In such a case, modal dispersion is normally much larger than chromatic dispersion. Therefore, minimizing modal dispersion of the multimode operation in the new optical fiber is indispensable.
1.4 Structure of Doctoral Thesis

As described in the previous section, required transmission characteristics of innovative optical fibers that overcome the capacity limit of the conventional single-mode fibers are low transmission loss, flexible chromatic dispersion, large effective area and low bending loss.

In those transmission characteristics, PCFs are very attractive transmission media since PCFs can provide unique dispersions and the wavelength dependence of mode field diameter (MFD) that are not obtainable in conventional single-mode fibers. The intrinsic loss is estimated to be less than that of the conventional single-mode fiber and bending loss characteristics are superior to those of a conventional single-mode fiber.

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 a small bending radius by technicians and customers.

Another alternative is to use multimode optical fiber because it has much large effective area compared with single-mode optical fibers and mode division multiplexing (MDM) will add another dimension to enlarge capacity of transmission system. In the deployment history, multimode optical fiber was given up because of large modal dispersion and modal noise problem. However, development of digital signal processing (DSP) technology makes it possible to utilize a few number of multi-input multi-output (MIMO) processing in transmission systems using the multimode fibers (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.

Figure 1-4 summarizes the structure and study items of three kinds of innovative optical fibers studied in this doctoral thesis.

![Figure 1-4 Study items of doctoral thesis](image)

Chapter 2 describes the ultra-low loss and long length photonic crystal fiber to replace conventional single-mode optical fibers. First, low loss PCF design parameters for reducing a confinement loss and the fabrication technology for the long length PCF with a low loss are described. Reducing the OH absorption loss of the PCF that is really necessary for WDM transmission system is also described. Moreover, it is clarified that the fabricated PCF can be applied to a dense wavelength division multiplexing (DWDM) transmission experiment.

Chapter 3 describes a HAPCF with a good bending performance for an optical wiring. First, the requirements of the mechanical
properties, connection loss and long-term reliability for the indoor optical wiring are clarified and a type of PCF is selected for a practical optical wiring use. Next, the HAPCF design is described. Then, the long-term reliability of the fiber is calculated. Finally, connection loss between the HAPCF and the conventional single-mode fiber is measured. It is clarified that the HAPCF can be a promising candidate for indoor wiring applications.

Chapter 4 describes a graded index two-mode optical fiber (TMF) with a low DMD, a large $A_{\text{eff}}$ and a low bending loss. First, fiber design for realizing the low DMD and low bending loss, and maximizing $A_{\text{eff}}$ is described. Next, the measured properties of fabricated fiber are compared with the calculated ones. Finally, the mode-launch characteristics for TMF are calculated by using the finite element-beam propagation method (FE-BPM) and the calculated results are compared with the experimental ones. It is clarified that GI-TMF design is suitable to MDM systems and the proposed TMF has a potential to reduce MIMO-DSP complexity.

Chapter 5 summarizes the results obtained in this study.
Chapter 2

Ultra-low Loss and Long Length Photonic Crystal Fiber

2.1 Introduction

Optical fibers with silica-air microstructures called photonic crystal fibers (PCFs) are very attractive transmission media since PCFs can provide unique dispersions and mode field diameters that are not obtainable in conventional single-mode fibers [14], [15]. The intrinsic loss of a PCF, which is composed of Rayleigh scattering and infrared absorption losses, is estimated to be less than that of a typical single-mode fiber since a PCF is composed only of a pure silica glass.

Since the first wave of PCFs, the optical attenuation has been reduced rapidly in the past years [16]–[18]. The lowest loss ever reported before this work was 0.58 dB/km and was achieved by increasing the scale of the PCF structure [19]. The optical attenuation is still high compared with that of a conventional single-mode fiber and the fiber length was limited to a few kilometers.
In this chapter, the structural parameters of PCF, hole diameter and hole pitch are designed in order to realize low loss PCFs. According to the design, PCFs are fabricated.

In Sec. 2.3, the loss spectra of fabricated PCFs are analyzed. Based on the spectral analysis of optical losses in PCFs, the fabrication technology during preform and drawing processes are improved to reduce the optical loss. The ultra-low loss and long length PCF utilizing the improved fabrication technology are fabricated.

In Sec. 2.4, the possibility of reducing the OH absorption loss of a PCF that is really necessary for WDM transmission system and to replace conventional single-mode optical fiber by PCF is shown.

Moreover, in Sec. 2.5, a dense wavelength division multiplexing (DWDM) transmission experiment by using the fabricated PCF are demonstrated.
2.2 Fiber Parameters and Fabrication

In PCFs, light is confined within a core region by holes. Light will move away from the core if the confinement provided by the holes is inadequate. This means the PCF structure as a hole diameter and a hole pitch have to be properly designed in order to realize low loss PCFs. The ratio of the hole diameter (d) to the hole pitch (Λ) is chosen to be large enough to confine light in the core. On the other hand, a large d/Λ makes the PCF multimode. By properly designing the structure, the confinement loss of single-mode PCFs can be reduced to a negligible level [20]. PCFs with 5 rings and 90 holes have been fabricated to sufficiently reduce the confinement loss to the ignorable level.

The high purity silica glass made with the vapor phase axial deposition (VAD) technique was selected. The intrinsic loss of the bulk glass, which is composed of the Rayleigh scattering and the infrared absorption losses, is estimated to be 0.14 dB/km at 1.55 μm wavelength [21].

Early works have shown that PCFs have a high Rayleigh scattering coefficient even though pure silica glass is used [18]. The reason for this high value can be attributed to the roughness of the hole interior surface. When stacking the rods and capillaries in the multi capillary method, small scratches and contamination can be introduced on the surfaces. These cause additional loss. In order to reduce the optical attenuation, the polishing and etching process is improved. Another useful technique is to increase the mode field diameter so that the surface roughness of the hole does not contribute to imperfection loss.

The PCF preforms were drawn into the optical fiber with a diameter of 125 μm in a carbon furnace. Fiber diameter fluctuations
during fiber drawing process were observed to be less than 1 µm.
2.3 Optical Properties of Low-loss PCF

Figure 2-1 shows the loss spectrum for a 10-km length of the fabricated low loss PCF. The optical loss was measured by the cutback technique. The inset shows the fiber cross section. The PCF with 90 holes had a hole diameter $d$ of 2.5 µm and a hole pitch $\Lambda$ of 4 µm. The hole diameters and hole pitches both at the starting and ending regions were measured. The difference of $d$ and $\Lambda$ between the starting and ending regions of the PCF were within 1%. The optical time domain reflectometry (OTDR) results show that there is no discontinuity along the entire length. The optical attenuations at 1.31 µm and 1.55 µm wavelengths were 0.37 and 0.71 dB/km, respectively.

![Figure 2-1 Loss spectrum of fabricated low-loss PCF](image)
Chromatic dispersion of the PCF was estimated from a wavelength dependence of pulse delay using super continuum picosecond pulses generated in an optical fiber [22]. Figure 2-2 shows the chromatic dispersion of the PCF with a length of 1 km. The zero dispersion wavelength was 950 nm and the chromatic dispersion at 1.55 µm wavelength was 76 ps/km/nm.

![Figure 2-2 Chromatic dispersion characteristics of fabricated low-loss PCF](image)

Several samples of PCF with the different surface roughness on the inner wall of the hole have fabricated. Each PCF has the same dimension of the structural parameters d/Λ = 0.6 and Λ of 4.0 µm. Each fabricated PCF had a fiber length of over 10 km. The optical loss spectra of these two fibers are shown in Fig. 2-3. The improved polishing and etching technique was applied to Fiber A to reduce the
surface roughness of holes. In contrast, Fiber B was fabricated with conventional treatment of surface roughness. The resultant surface roughness for Fibers A and B was estimated to be several nanometers and several tens of nanometers respectively. It was clarified that the different fabrication processes was responsible for the differences of optical loss properties.

The confinement loss for these structures was calculated and it was estimated to be 0.01 dB/km for a wavelength region between 1.0 and 1.7 µm. Fiber diameter fluctuations for these fabricated fibers were within 1 µm. The loss $\alpha$ (dB/km) is well fitted to the following Eq. (2-1)

$$\alpha(dB/km) = \frac{A}{\lambda^2} + B + \alpha_{OH} + \alpha_{IR} \quad (2.1)$$

where A and B denote Rayleigh scattering coefficient and the imperfection loss, respectively. $\alpha_{OH}$ and $\alpha_{IR}$ are the OH absorption and the infrared absorption losses, respectively.

Table 2-1 shows the comparison of loss components calculated with a nonlinear fitting technique. The infrared absorption loss component for Fibers A and B, which is a part of the intrinsic loss, was almost equal to the intrinsic level.

From Table 2-1, the main loss differences between Fibers A and B were the Rayleigh scattering and imperfection losses. Another high extrinsic loss was OH absorption loss. It has a peak at 1.38 µm and contributes loss of 0.12 dB/km at 1.55µm. This is extremely high compared with that of a conventional single-mode fiber and obviously affects the optical properties.

In order to further reduce the optical loss of the PCF, the process has to be improved so as to avoid the inclusion of OH ion. The optical loss of PCF will reduce to be 0.25 dB/km at 1.55µm if the OH
ion can be removed.

By further improvement of the process such as reduction of surface roughness, it is expected that the Rayleigh scattering and the imperfection losses due to the roughness can be reduced. If these excess losses can be eliminated, the optical loss of PCF becomes that of a silica glass, which is less than that of a conventional single-mode fiber.
Figure 2-3 Loss spectra of low loss and conventional PCFs

Table 2-1 Comparison of loss components

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<tr>
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<th>Fiber B</th>
<th>Fiber C</th>
<th>Conventional SMF</th>
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<tr>
<td>Loss @1.31(\mu m), dB/km</td>
<td>0.71</td>
<td>2.72</td>
<td>1.61</td>
<td>0.35</td>
</tr>
<tr>
<td>Loss @1.55(\mu m), dB/km</td>
<td>0.37</td>
<td>1.97</td>
<td>1.20</td>
<td>0.2</td>
</tr>
<tr>
<td>Rayleigh scattering Coefficient, dB/km/(\mu m^4)</td>
<td>1.0</td>
<td>2.3</td>
<td>1.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Imperfection loss, dB/km</td>
<td>0.07</td>
<td>1.49</td>
<td>0.90</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>OH absorption loss @1.55(\mu m), dB/km</td>
<td>0.12</td>
<td>0.12</td>
<td>0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Ir absorption @1.55(\mu m), dB/km</td>
<td>0.012</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
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2.4 Trial of the PCF Water Peak Reduction

In the fiber, the major component of optical attenuation was OH absorption loss. Several experiments were performed to improve the dehydration process. The OH impurities in a PCF are composed of the inherent OH impurities in a raw silica glass and those on the surface of the holes which diffuse into the core region of the PCF at high temperature during fabrication process. First, a high purity silica glass was selected. The high purity silica glasses used in the measurements are made by the VAD technique. Special precautions were taken during both the preform preparation and fabrication process to prevent the water from entering the air hole. The OH absorption loss of the glass preform at 1.38 µm wavelength was determined to be less than 0.5 dB/km, which was estimated from the dehydration condition in the VAD technique.

Figure 2-4 shows the loss spectrum of fabricated low OH absorption PCF (Fiber C). The loss spectrum of Fiber B is shown in the same figure. The structural parameters are the same as those of Fibers A and B.

Fiber C has an OH absorption loss as low as 3 dB/km. The loss value is almost half of that of previously reported PCF to the best of our knowledge in 2003 [23]. It is obvious that excluding water from the holes, during the fabrication process is essential to reduce the OH absorption loss.

The optical attenuations of Fiber C at the 1.55µm wavelength was 1.2 dB/km. Unfortunately, the PCF fabrication process has not been fully optimized at this time. The high attenuation is caused mainly by surface roughness of the hole along the entire fiber length. Further reduction of the roughness in the process is needed to reduce the optical attenuation.
Figure 2-4 Loss spectra of low OH absorption and conventional PCFs
2.5 DWDM Transmission Experiment

The fiber A was used to perform a 10 Gbit/s x 8 channel DWDM transmission experiment. The experimental setup is shown in Fig. 2-5. The eight wavelength outputs from 192.7 to 193.4 THz with 100 GHz channel spacing from external cavity lasers were multiplexed, and simultaneously modulated using a LiNbO3 intensity modulator driven by $2^{11} - 1$ non return-to-zero (NRZ), pseudorandom bit stream. After optical amplification, the transmitter output signal was launched into the PCF. The output signal from the 10-km length PCF was de-multiplexed to each channel and the bit-error rate (BER) was measured.

The BER measurement results for eight channels are shown in Fig. 2-6. Power penalties for BER of $10^{-11}$ were from 0.4 to 1.3 dB for eight channels. No sign of an error floor for any of the eight different wavelength channels were observed.

![Figure 2-5 DWDM transmission experiment set up](image)
Figure 2-6 BER measurement result of DWDM transmission experiment
2.6 Conclusion

The structural parameters of PCF, the hole diameter, hole pitch to reduce its optical loss were designed. Then, some different kinds of PCFs were fabricated with the same dimension of the geometrical parameters according to the fiber design and, the different surface roughness on the inner wall of the hole. The loss spectra of the fabricated PCFs were analyzed. Based on the spectral analysis of optical loss in PCFs, the fabrication technology during the preform and drawing fabrication processes were improved. As a result, the low-loss photonic crystal fiber with a loss of 0.37 dB/km at 1.55μm and fiber length of 10km was successfully realized. Reducing the OH absorption peak loss of PCF to 3 dB/km was also realized by excluding water from the holes during the preform and fabrication processes. Moreover, the transmission of WDM signals of 8 x 10 Gbit/s by using the fabricated PCF with a length of 10 km was successfully demonstrated.

The improved fabrication technology will be applied to the low loss and long length PCFs. All of these results also confirmed that PCF will be one of promising candidates in transmission medium for telecommunication networks.
Chapter 3

Hole-assisted Type Photonic Crystal Fiber with Good Bending Loss Performance

3.1 Introduction

In recent years, transmission capacity has increased rapidly due to the introduction of various kinds of broadband services. Fiber To The Home (FTTH) is the most promising approach for meeting the demand for high-speed services because of its large transmission capacity and symmetrical up-down speed. In 2002, NTT (Nippon Telegraph and Telephone Corporation from 1985) launched an FTTH service named B-FLETS in Japan, and FTTH is currently being widely spread. For the installation of FTTH, indoor optical wiring is one of the most important problems. This is because indoor optical wiring provides a shorter transmission line but has more connection and bending points. This makes it necessary to choose a suitable optical fiber for this purpose.

Recently, a photonic crystal fiber (PCF) with a silica-air microstructure has received increasing attention because of its novel
guiding properties, which suggest the possibility of diverse optical transmission applications [24, 25]. Of its features, its low bending loss is considered to make it suitable for use as an optical wiring in residential and business premises.

In this chapter, applicability of the hole assisted type PCF (HAPCF) to the indoor wiring is studied. First, general requirements for the indoor wiring are analyzed. Then, the structure of PCF that is suitable to indoor wiring is selected by taking into account the analysis.

In Sec. 3.3, bending loss characteristics of HAPCF is studied because there are a lot of bending points in indoor wiring and attenuation of bending loss cannot be ignored. Calculation model of HAPCF is defined and the near field pattern based on that model is calculated to confirm that near field pattern is confined in HAPCF compared with the conventional single-mode optical fiber or not. Furthermore, the bending characteristics of HAPCF are confirmed by calculations and measurements.

The long-term reliability of HAPCF is also investigated because there are a lot of bending points and smaller bending radius is expected in the indoor wiring.

To consider the actual deployment, connection between the HAPCF to the conventional SMF will be necessary. The reasonably low connection loss is needed. The fusion splice and mechanical splice connection loss characteristics for HAPCF are measured.
3.2 Consideration of PCF Applied to Optical Wiring

3.2.1 Requirements for Indoor Optical Wiring

Figure 3-1 shows a typical indoor optical wiring configuration. This wiring covers the area from a cabinet to an optical network unit (ONU) and is expected to extend to a user terminal. There are several types of optical fiber cable used in this area, including the indoor optical fiber cable, the termination optical fiber cable, the indoor riser fiber cable, and the floor distribution fiber cable.

The general requirements for the indoor optical wiring are listed in Table 3-1. The fiber for the indoor optical wiring is expected to have the same characteristics as the conventional optical fiber, furthermore it requires a smaller bending loss against a smaller bending radius and sufficient reliability. Additionally, because there are more connection points installed in the indoor wiring areas, it must also have good connection performance.
Table 3-1 Requirements for indoor wiring

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Stable and low loss of pulling, bending, and lateral pressure characteristics</td>
</tr>
<tr>
<td>Connection</td>
<td>Easy operation and low connection loss</td>
</tr>
<tr>
<td>Long term reliability</td>
<td>Long lifetime</td>
</tr>
<tr>
<td>Others</td>
<td>Good appearance, ease of handling</td>
</tr>
</tbody>
</table>
3.2.2 Structure of PCF for Indoor Optical Wiring

PCFs have several different kinds of structure and all have periodically arranged holes along the fiber. Table 3-2 shows three types of PCF reported over the past years.

Type A is photonic band-gap type PCF (PBGF), which has an air hole as its core and holes in its cladding arranged to form two dimensional photonic crystals. PBGF guides light by the photonic band gap effect. Several years have passed since a true band-gap fiber was fabricated [26], but the optical loss of PBGF is still too large for a practical use.

Type B [27] and Type C [28] are both index guiding type PCF (IGPCF). Although these kinds of fiber are also called PCF, their guiding properties do not rely on photonic band gap effect but on total internal reflection (TIR) of the conventional mechanism. PCF of Type B is made from mono material and Type C has a high refractive index core. Periodically arranged holes in the cladding reduce its effective refractive index, and the refractive index of the core is larger than that of the cladding so the light is guided by the TIR effect.

It should be noted that Type C has a high refractive index core, so the air holes in the cladding simply assist the control of the optical properties. Because of this property, Type C is also called hole assisted type PCF (HAPCF).

Recent PCF studies have mainly focused on IGPCF because the strict periodicity of the hole is not required in order to realize wave-guide. The lowest optical loss of 0.37dB/km has been reported for IGPCF [29]. For Type B, a large connection loss, equivalent to optical attenuation of several km length of the fiber is thought to be induced
when the fusion splice method is used, because of the destruction of the wave-guide structure. In contrast, the connection loss is expected to be smaller than HAPCF because the air holes do not play a major role of the wave-guide.

HAPCF is particularly attractive for the indoor optical wiring when taking the high bending loss performance, mass productivity and low connection loss into consideration. In this chapter, the possibility of using HAPCF for the indoor optical wiring is mainly investigated.

Table 3-2 Photonic crystal fiber

<table>
<thead>
<tr>
<th>Type</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photonic band gap type</td>
<td><img src="image" alt="Diagram A" /></td>
</tr>
<tr>
<td>A</td>
<td><img src="image" alt="Diagram B" /></td>
</tr>
<tr>
<td>Index guiding type</td>
<td><img src="image" alt="Diagram C" /></td>
</tr>
<tr>
<td>B</td>
<td><img src="image" alt="Diagram D" /></td>
</tr>
<tr>
<td>C</td>
<td><img src="image" alt="Diagram E" /></td>
</tr>
</tbody>
</table>
3.3 Optical Properties of HAPCF

3.3.1 Calculation Model

Figure 3-2 shows the cross-sectional structure of HAPCF. There is a conventional high refractive index core in the center of the fiber with a radius of \( a \). Several holes of diameter \( d \) are formed periodically in the cladding around the core, and the distance between the core center and the hole circumference is defined as \( c \). The distance between the fiber center and the hole center is defined as \( r \), and the fiber radius is defined as \( r_f \).
3.3.2 Near Field Pattern

Figure 3-3 shows the calculated near field distribution of normal single-mode fiber (SMF) and two types of HAPCF. All these fibers are assumed to have the same dimensions ($a=5\mu m$, $r_f=62.5\mu m$) and core refractive index. The calculations were performed with the finite element method (FEM) at a wavelength of 1550 nm. The HAPCF hole positions $c/a$, ratio of core diameter $a$ and the distance between the core center and the hole circumference $c$ are 1.2 and 2 respectively. The each line in Fig. 3-3 shows the equi-intensity of the near field pattern. From Fig. 3-3, it is clear that the near field pattern is confined by the existence of the holes.

Figure 3-3 Near field pattern
3.3.3 Bending Loss Performance

The bending loss characteristics of HAPCF were investigated both numerically [30] and experimentally. Actual effective refractive index at the hole area is parabolic. Here the effective refractive index at a specified radius is simply approximated as the average of the refractive index on the hole area. The inset in Fig. 3-4 shows the effective refractive index profile of HAPCF, which is W-type index profile.

Figure 3-4 shows the calculated bending loss characteristics for SMF and two types of HAPCF at a wavelength of 1550 nm. It is obvious that the HAPCF with large hole (d=0.8a) and HAPCF with small hole (d=0.4a) has lower bending loss than conventional SMF for the same bending radius. Furthermore, it is also found that an increase in the hole size reduces the bending loss. The bending loss characteristics of the fabricated HAPCF (c/a=1.2, c/a=2, a=5μm, d=2a) and conventional SMF were measured. The bending loss experiments were performed with a bending radius of 10 mm and 20 turns.

The measurement results are shown in Fig. 3-5. This figure shows that the optical loss of SMF increased more than 5 dB at the wavelengths more than 1500 nm. In contrast, for HAPCF the loss increase was negligible (<0.01 dB) over the whole wavelength range from 1300 to 1600 nm. Thus the outstanding bending loss performance of HAPCF was confirmed by the measurement.
Figure 3-4 Calculated bending loss

Figure 3-5 Measured bending loss
3.4 Long-term Reliability

Long-term reliability is an important issue as regards fiber for practical use. The flaw distribution on the air hole surface is assumed to be the same as that on the fiber surface. The fiber is assumed to have passed a proof test where the test stress and time are $\varepsilon_p$ and $t_p$, respectively. The cumulative failure probability $F$ after time $T_0$ can be expressed by Eq. (3-1). [31][32][33]

$$F = \exp \left\{ -N_p L_0 t_0 \frac{1}{\varepsilon_p n_p} r_f + \frac{1}{L_0} \int_{t_0}^{t} \frac{1}{T_0} \left( \frac{m}{\varepsilon_p n_p} n_1 - 2 \pi r_f \right)^{2^n} d\theta_i \right\}$$

$$+ \frac{1}{\varepsilon_p n_p} r_f - 2 \sum_{s=1}^{N} \int_{4\pi}^{2\pi} \int_{0}^{\varepsilon_s} d\theta dt$$

(3-1)

where $N_p$ is the failure number per unit length, $L_0$ is the length of the fiber, $r_f$ is the fiber radius, $N$ and $d$ are the number and diameter of the hole, $m$ is a constant related to the initial inert strength distribution, and $n_1$ and $n_2$ are constants determined by the material and environment of the fiber and hole surface, respectively.

$\varepsilon_f$ and $\varepsilon_h$ are the strains on the fiber and the hole surface, respectively. These strains are a combination of the cabling residual strain $\varepsilon_1$, construction strain $\varepsilon_2$, construction residual strain $\varepsilon_3$, temperature variation strain $\varepsilon_4$ and bending strain $\varepsilon_5$. The value of each type of strain, the strain length and time are shown in Table 3-3.

The bending strain $\varepsilon_5$ on the fiber and air hole surfaces can be expressed by Eqs. (3-2) and (3-3) respectively.

fiber surface: $\varepsilon_5 = \frac{r \sin \theta}{R}$

(3-2)

air hole surface: $\varepsilon_5 = \frac{r \sin \theta \left[ \frac{2\pi(S-1) + \theta_1}{N} \right] + \frac{d}{2} \sin \theta}{R}$

(3-3)
where \( R \) is the bending radius and \( r \) is the distance between the center of the fiber and the center of the hole.

The predicted lifetime of the fiber with the values \( \varepsilon_p = 1.0\% \), \( t_p = 1s \), \( N_p = 0.1 \text{ km}^{-1} \), \( L_0 = 300\text{ m} \), \( r_f = 62.5 \mu\text{m} \), \( N = 6-10 \), \( d = 8-16 \mu\text{m} \), \( m = 3 \), \( n_1 \) and \( n_2 = 20 \) and assuming the number of 90-degree bends to be 40 was calculated. Figure 3-6 shows the calculated results. It is found from Fig. 3-6 that the existence of the holes does not greatly affect the long-term reliability. From the experience of conventional fibers, it is possible to improve the long-term reliability of the fiber by increasing the proof test strain or value of \( n \) by carbon coating. It is considered that same results can be obtained in HAPCF. With extremely low bending loss characteristics, HAPCF can be used in severe circumstance like the bending radius is as small as 10 mm if long-term reliability is improved. The predicted lifetime of fiber with the values \( N = 6 \), \( d = 8 \mu\text{m} \), \( r = 15 \mu\text{m} \), \( \varepsilon_p = 1.5\% \), \( n_1 = 100 \) was calculated. The results are also shown in Fig. 3-6. By using a suitable pre-process it is possible to improve the lifetime of optical fiber so that it can be used with a 10 mm bending radius.

### Table 3-3 Strain components in optical fiber

<table>
<thead>
<tr>
<th>Component</th>
<th>Strain (%)</th>
<th>( L/L_0 )</th>
<th>( T/T_0 )</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabling residual strain ( \varepsilon_1 )</td>
<td>0.05K</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Construction strain ( \varepsilon_2 )</td>
<td>0.20K</td>
<td>1</td>
<td>( 7200/T_0 )</td>
<td>Construction time 2 hours</td>
</tr>
<tr>
<td>Residual strain due to construction ( \varepsilon_3 )</td>
<td>0.02K</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Strain due to temperature variation ( \varepsilon_5 )</td>
<td>0.03K</td>
<td>1</td>
<td>1</td>
<td>Half year</td>
</tr>
<tr>
<td>Bending strain ( \varepsilon_4 )</td>
<td>Eqs. (3-2) and (3-3)</td>
<td>( N_5 \pi R/2 )</td>
<td>( 1.58\times10^7/T_0 )</td>
<td>Calculation of 90 degree bends</td>
</tr>
</tbody>
</table>

\( n_b \): number of 90 degree bends
\( K \): \( r_f^2/(r_f^2\cdot N_r^2) \)
Figure 3-6 Relationship between predicted lifetime and bending radius
3.5 Connection Loss

Another important characteristic, namely the connection loss was also investigated. The fusion splice and mechanical splice connection loss characteristics for HAPCF to HAPCF and HAPCF to SMF connection were measured. The experimental results are shown in Figs. 3-7 and 3-8. Here, the HAPCF has the structure shown in Fig. 3-2 where $c=2a$, $d=2a$, $a=5\mu m$ and almost same MFD with conventional single-mode fiber as shown in Fig. 3-3 (b). The experiments with the conventional SMF connection methods were performed and no special modifications to the connection method or tool were made.

The measurement results show that the connection loss was no more than 0.5 dB for both the fusion splice and mechanical splice methods, and indicate that it is possible to connect the HAPCF with the conventional connection methods and tools.

![Figure 3-7 Fusion splice loss](image-url)
Figure 3-8 Mechanical splice loss

Wavelength 1.3μm
- SMF-HAPCF
  - Average: 0.27dB
  - Standard deviation: 0.08dB
- HAPCF-HAPCF
  - Average: 0.31dB
  - Standard deviation: 0.08dB
3.6 Conclusion

Applicability of hole assisted type PCF (HAPCF) to the indoor wiring was studied. General requirements for the indoor wiring were analyzed and found that smaller bending loss against a smaller bending radius and sufficient reliability are absolutely necessary characteristics. Good connection performance is also required because there are many connection points installed in the indoor wiring areas. Then, HAPCF was selected as the suitable structure of PCF for the indoor wiring in consideration of those requirements.

In Sec. 3.3, bending loss characteristics of HAPCF was studied. Calculation model of HAPCF was defined and near field pattern was calculated based on that model. It was confirmed that near field pattern is confined in HAPCF compared to conventional single-mode optical fibers. Furthermore, HAPCF is confirmed to be superior bending loss characteristics by calculation and measurements. The loss increase for SMF was more than 5 dB over the whole wavelength range from 1500 to 1600 nm with a bending radius of 10 mm and 20 turns. In contrast, the loss increase for HAPCF was negligible (<0.01 dB) at the same conditions.

In Sec. 3.4, long-term reliability of HAPCF was investigated. From the calculated results, it was found that the existence of the holes does not greatly affect the long-term reliability. The predicted lifetime of HAPCF was also calculated at the bending radius is as small as 10 mm. The results showed that HAPCF is able to achieve more than 20 years lifetime with a 10 mm bending radius by increasing the proof test strain or by carbon coating.

Finally, the fusion splice and mechanical splice connection loss characteristics for HAPCF to HAPCF and HAPCF to SMF connection were measured. The connection loss measurement results suggested that
it is possible to apply conventional connection technology to HAPCF with acceptable connection loss levels.

Based on the above results, it was concluded that hole-assisted type PCF could deploy for indoor optical wiring applications.
Chapter 4

Graded Index Two-mode Optical Fiber with Low DMD, Large $A_{\text{eff}}$ and Low Bending Loss

4.1 Introduction

The traffic of backbone network has been increasing rapidly corresponding to the growth of broadband users in worldwide. It is reported that the current system utilizing the conventional single-mode optical fibers (SMFs) will approach the limit of input power, which is directly related to the transmission capacity in the wavelength division multiplexing (WDM) system, because of the optical nonlinear effects and the fiber fuse [34]. For next generation system, mode division multiplexing (MDM) transmission system using a few-mode fiber (FMF) has been studied actively [35-42].

In the MDM system, multiple-input-multiple-output (MIMO) digital signal processing (DSP) can be applied to recover the transmitted signals. However, it is known that differential modal group delay (DMD) of FMF increases DSP complexity [35-39]. Then, FMF
with low DMD would have advantage to be applied to MDM utilizing the MIMO. Low DMD in the wide wavelength range is required for the WDM applications. Moreover, low bending loss of not only fundamental mode but also higher order modes is essential. Furthermore, enlargement of the effective area ($A_{\text{eff}}$) is also desirable for increasing the launched power into the fiber, resulting in increase of the multiplicity of WDM.

It is known that FMF with a graded index (GI) profile minimizes DMD [36, 38-40]. Reference [36] shows the FMF with both of low DMD and low mode coupling, Reference [39] and [40] shows the optimal value of $\Delta$ and $\alpha$ to minimize DMD. However, there has been no report on FMF design optimizing DMD, bending loss and $A_{\text{eff}}$.

In this chapter, a fiber design which optimizes the DMD, bending loss and $A_{\text{eff}}$ in graded-index type few mode fibers as one of the innovative optical fibers is investigated. The two mode fibers (TMFs) with a GI index profile are fabricated and the transmission characteristics of the fabricated TMFs are clarified. Moreover, mode launching characteristics by numerical simulation to estimate the mode coupling at a splice point with an offset is clarified.

In Sec 4.2, the suitable profile design of TMF with DMD = 0 ps/km, $A_{\text{eff}} \geq 150 \mu m^2$ for LP$_{01}$ mode, and bending loss for LP$_{11}$ mode $\leq 0.01$ dB/km at R = 40 mm at the wavelength of 1550 nm is clarified.

Refractive index profile, $A_{\text{eff}}$, cutoff wavelength, attenuation of LP$_{01}$ mode, bending loss for LP$_{11}$ mode at R = 40 mm and chromatic dispersion of the fabricated GI-FMF are measured.

From the experience of GI multimode fiber, mode coupling at the splice point may degrade the transmission quality. Mode launch characteristics for TMF is calculated by using finite element-beam propagation method (FE-BPM) and the validity and usefulness of the
present approach are shown by comparing with experimental results.
4.2 Fiber Design

Figure 4-1 shows the refractive-index profile of the graded index (GI) fiber. The GI profile is given by

$$n(r) = \begin{cases} n_1[1-2\Delta(r/a)^\alpha]^{1/2} & 0 \leq r \leq a \\ n_2 & r \geq a \end{cases}$$ (4-1)

Figure 4-1 Refractive index profile of the graded index fiber

where \(n_1\) and \(n_2\) are the indices of the core and the cladding, respectively, \(r\) is the distance from the center of the core, \(a\) is the core radius, and \(\alpha\) is the index profile parameter. \(\Delta\) is the relative-index difference between the core and the cladding, which is defined as

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$ (4-2)

Next the fiber parameters of TMF are designed. The requirements of TMF that DMD = 0 ps/km, \(A_{eff} \geq 150 \mu m^2\) for LP\(_{01}\) mode, and bending loss for LP\(_{11}\) mode \(\leq 0.01\) dB/km at \(R = 40\) mm at the wavelength of 1550 nm are determined. Bending loss at \(R = 40\) mm is an equivalent condition for microbending loss in the cable [43]. This value is the important factor to evaluate the cabling adaptability of optical fibers. In addition, bending loss was evaluated with simulation
using finite element method [44] and other characteristics were calculated by multilayer division method [45].

Figure 4-2 shows the relationship between the normalized frequency $T$ and the calculated DMD at 1550 nm for the different $\alpha$ and $\Delta$. Here, DMD is defined as $1/v_{g11} - 1/v_{g01}$, where $v_{g11}$ and $v_{g01}$ are the group velocities of LP$_{11}$ and LP$_{01}$ modes, respectively. Normalized frequency $T$ is defined by

$$T = k\text{an}_1\sqrt{2\Delta}/A$$  \hspace{1cm} (4-3)$$

where $k$ is the wave number and $A$ is a constant value depending on the refractive index profile. Because $\Delta$ and wavelength are kept to be constant in Fig.4-2, increase of $T$ means an increase in the core radius. The cutoff frequencies of LP$_{11}$ and LP$_{21}$ (or LP$_{02}$) modes are calculated. It is known that the normalized cutoff frequency of the LP$_{02}$ mode of the GI fiber with $\alpha$ of 2 is smaller than that of the LP$_{21}$ mode and it is also clear that the normalized cutoff frequencies of two modes depend on the refractive index profile. For the step-index fiber, the normalized cutoff frequency of LP$_{21}$ mode is smaller than that of LP$_{02}$ mode. Moreover, as the difference of the normalized cutoff frequency between LP$_{02}$ and LP$_{21}$ modes is very small, the two mode condition is described in the paper where the cutoff frequency is smaller than that of LP$_{21}$ mode. Since the cutoff frequencies $T$ for GI fiber with different $\alpha$ of LP$_{11}$ and LP$_{21}$ modes are obtained to be 2.5 and 4.5, two-mode propagation region is $2.5 \leq T < 4.5$. It was confirmed from Fig. 4-2 that DMD is almost independent of $\Delta$ in the range of 0.3% to 0.4% and that two mode propagation with DMD of 0 ps/km is satisfied for $\alpha \geq 2.2$. In addition, the smaller $\alpha$ is, the smaller DMD slope at the normalized frequency of zero DMD is. This means that the value of DMD can be reduced in the whole C band as $\alpha$ become smaller. Figure 4-3 shows the maximum value of DMD for $\alpha$ over the entire C band. It is obvious that the maximum DMD value become smaller as $\alpha$ is smaller. However,
because the LP$_{21}$ mode would propagate in $\alpha \leq 2.2$, the appropriate range of $\alpha$ is $2.2 \leq \alpha \leq 2.4$.

![Figure 4-2 DMD characteristics of GI at 1550 nm](image)

Figure 4-2 DMD characteristics of GI at 1550 nm

![Figure 4-3 Maximum value of DMD for $\alpha$ over the entire C band](image)

Figure 4-3 Maximum value of DMD for $\alpha$ over the entire C band
Figure 4-4 shows calculation results of bending loss for LP\textsubscript{11} mode at R = 40 mm at 1550 nm where DMD = 0 ps/km. It is obvious that the bending loss decreases as $\Delta$ increase. On the other hand, the bending loss decreases as $\alpha$ decrease. The reason is that core radius at the point of DMD = 0 ps/km increases as $\alpha$ decreases. Figure 4-5 shows the calculation results of $A_{\text{eff}}$ for LP\textsubscript{01} mode at 1550 nm and DMD = 0 ps/km. $A_{\text{eff}}$ increases as $\Delta$ and $\alpha$ decrease. According to the result of Figs. 4-5, low DMD in the C band and good bending characteristics and large $A_{\text{eff}}$ can be obtained by decreasing $\alpha$ keeping DMD = 0 ps/km. With the calculation results from Figs. 4-2, 4-4 and 4-5, the region satisfying our requirements, that is DMD = 0, $A_{\text{eff}} \geq 150 \mu m^2$ for LP\textsubscript{01} and bending loss for LP\textsubscript{11} $\leq 0.01 \text{ dB/km}$ at R = 40 mm at 1550 nm, is the hatched area in Fig. 4-6. The center of the hatched area is shown by the circle in Fig. 4-6. The fiber parameters on the center are $\Delta = 0.36\%$, core radius $a = 11.8 \mu m$ and $\alpha = 2.3$. The DMD at 1550 nm is 0 ps/km.

![Graph showing the relationship between $\Delta$ and bending loss for LP\textsubscript{11} mode at 1550 nm as a function of $\alpha$.]
Figure 4-5 Relationship between $\Delta$ and $A_{\text{eff}}$ for LP$_{01}$ at 1550 nm as a function of $\alpha$.

Figure 4-6 Region satisfying requirements (DMD=0 at 1550 nm, $A_{\text{eff}} \geq 150 \mu m^2$ for LP$_{01}$ and bending loss for LP$_{11} \leq 0.01$ dB/km at R = 40 mm).
4.3 Characteristics of Fabricated Fiber

4.3.1 Refractive Index Profile

Figure 4-7 shows the refractive-index profile of the fabricated GI-TMF measured by the refractive near field pattern (RNFP) method [46]. The broken line shows the fitted line to Eq. (4-1) with the least square method of the fabricated GI-TMF. Table 4-1 summarizes the structural parameters of the fabricated GI-TMF based on the fitting curve. Though a small central dip was formed, almost designed structural parameters were obtained.

![Figure 4-7 Refractive index profile of fabricated GI-TMF measured by RNFP. Broken line represents the fitted line by Eq. (4-1).](image)

Table 4-1 Structural parameters of the fabricated GI-TMF

<table>
<thead>
<tr>
<th></th>
<th>$\Delta$ [%]</th>
<th>$\alpha$</th>
<th>$a$ [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GI-TMF</td>
<td>0.363</td>
<td>2.29</td>
<td>11.6</td>
</tr>
</tbody>
</table>
4.3.2 Optical Properties of Fabricated GI-TMF

Table 4-2 shows optical properties of the GI-TMF at $\lambda = 1550$ nm. The properties of LP$_{01}$ mode were measured on bending to attenuate only LP$_{11}$ mode power. The properties of LP$_{11}$ mode except for bending loss were calculated using multilayer division method and the index profile measured by RNFP. Attenuation for LP$_{01}$ was 0.196 dB/km. The effective areas $A_{\text{eff}}$ of LP$_{01}$ and LP$_{11}$ modes were obtained to be about 150 $\mu$m$^2$ and over 200 $\mu$m$^2$, respectively.

Table 4-2 Optical properties of fabricated GI-TMF at $\lambda = 1550$ nm

<table>
<thead>
<tr>
<th></th>
<th>Mode</th>
<th>GI-TMF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>[m]</td>
<td>4870</td>
</tr>
<tr>
<td><strong>$A_{\text{eff}}$</strong></td>
<td>[\mu m$^2$]</td>
<td>LP$_{01}$ 149.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LP$_{11}$* 201.2</td>
</tr>
<tr>
<td><strong>Cutoff wavelength</strong></td>
<td>[nm]</td>
<td>LP$_{21}$ 1495</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LP$_{11}$* 2315</td>
</tr>
<tr>
<td><strong>Attenuation</strong></td>
<td>[dB/km]</td>
<td>LP$_{01}$ 0.196</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LP$_{01}$ 0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LP$_{11}$ 0.016</td>
</tr>
<tr>
<td><strong>Bending loss at R = 40 mm</strong></td>
<td>[dB/km]</td>
<td>LP$_{01}$ 0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LP$_{11}$ 0.016</td>
</tr>
<tr>
<td><strong>Chromatic dispersion</strong></td>
<td>[ps/km/nm]</td>
<td>LP$_{01}$ 20.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LP$_{11}$* 19.3</td>
</tr>
</tbody>
</table>

*calculated value
4.3.2.1 Measurement Result of Cutoff Wavelength

Cutoff wavelength was measured with 2m bend reference technique [47]. Measured spectral loss is shown in Fig. 4-8. Two peaks were observed in the wavelength range between 1400 to 2400 nm. The edges at longer wavelength of these peaks represent cutoff wavelengths of LP_{11} and LP_{21} modes because those cutoff wavelengths calculated with the index profile measured by RNFP were 1520 and 2315 nm, respectively. The cutoff wavelength of LP_{21} and LP_{11} modes were 1495 nm and over 2300 nm, respectively. That means the fabricated GI-TMF can transmit only LP_{01} and LP_{11} modes in C, L and U-band.

Figure 4-8 Measured spectral loss in bend reference technique
4.3.2.2 Measurement Result of Bending Loss for $LP_{11}$ Mode

Figure 4-9 shows the schematic diagram of the experimental setup. Bending loss for $LP_{11}$ mode was measured by exciting only $LP_{11}$ mode using offset-connecting to SMF with a light source of 1550 nm laser diode (LD) [48-50]. Offset was about 16 µm and $LP_{11}$ mode power was about 97% of the total input power. Bending loss of GI-TMF was measured with and without bend of radius $R_2$, under the bending condition of bend radius $R_1$ to eliminate leaky mode. The reason why bend radius $R_1$ added is because sample fiber length is only 3m and leaky mode can transmit such short length fiber. For the measurement of bending loss, minimum loss change of $10^{-3}$ dB can be evaluated and from a practical viewpoint, the maximum fiber length wound on the bobbin is about 1 m. In this case, the fiber with length of 1 km have to be wound on the bobbin with a radius of 40 mm but it is impossible. Even if the bending loss for the length of 1 m is evaluated, the bending loss at a radius of 40 mm is about $10^{-5}$ dB/km so that the bending loss cannot be measured by the current measurement system as mentioned above. Therefore, the bending loss is estimated by utilizing the well-known relationship between the logarithm of the bending loss in dB and the bending radius. Measured value of bending loss of $LP_{11}$ mode for $R_2= 15, 17$ and $20$ mm are shown by solid circles in Fig. 4-10. Solid line shows the bending property calculated by finite element method and the measured index profile. Calculated and measured results are in good agreement. Therefore, the bending loss of $LP_{11}$ mode with a radius of 40 mm can be estimated to be 0.016 dB/km from the calculated results as shown in Fig. 4-10.
Figure 4-9 Experimental setup of bending loss for LP_{11} mode measurement

Figure 4-10 Measured result of bending loss for LP_{11} at the radius of 15, 17 and 20 mm
4.3.2.3 Experimental Setup and Results of DMD

Figure 4-11 shows the experimental setup of the interference method for DMD measurement [51]. To excite the LP\(_{01}\) and LP\(_{11}\) modes, TMF was spliced with a single-mode fiber at the offset of 6.0 μm. Light sources were LEDs with center wavelength at 1300 nm, 1450 nm, 1550 nm and 1650 nm. The intensity of the interference pattern depends on the wavelength and is a nearly sinusoidal pattern.

Here, the relationship between the DMD and the measured wavelength period \(\Delta \lambda\) for FMFs are derived by following theoretical treatment. When the electromagnetic fields of the LP\(_{01}\) and LP\(_{11}\) modes coupled at \(z=0\) is given by \(E_{01}(z, t)\) and \(E_{11}(z, t)\), respectively, where \(z\) is the distance downstream from the FMF’s entrance face, the wave field at the FMF’s exit face is expressed as

\[
E_{01}(L, t) = A_{01} \exp \left\{ j[\alpha L - \beta_{01}(\omega) L] \right\}
\]

(4-4)

and

\[
E_{11}(L, t) = A_{11} \exp \left\{ j[\alpha L - \beta_{11}(\omega) L] \right\}
\]

(4-5)

where \(\omega\) is the center angular frequency of the light emitted from the source, \(t\) is the time, \(A_{01}\) and \(A_{11}\) are the amplitudes, and \(\beta_{01}(\omega)\) and \(\beta_{11}(\omega)\) are the propagation constants for LP\(_{01}\) and LP\(_{11}\) modes traversing the FMF of length \(L\), respectively. Focusing on phases \(\phi_{01}=\omega t - \beta_{01}(\omega) L\) and \(\phi_{11}=\omega t - \beta_{11}(\omega) L\) of the guided modes, the phase difference \(\phi(\omega)\) between \(\phi_{01}\) and \(\phi_{11}\) is written as

\[
\phi(\omega) = \phi_{11} - \phi_{01} = [\beta_{01}(\omega) - \beta_{11}(\omega)] L
\]

(4-6)

Furthermore, the difference \(\Delta \phi\) between \(\phi(\omega+\Delta \omega)\) and \(\phi(\omega)\) is approximated as follows,
$$\Delta \phi(\omega) = \phi(\omega + \Delta \omega) - \phi(\omega)$$
$$= \left[ \beta_{01}(\omega + \Delta \omega) - \beta_{11}(\omega + \Delta \omega) \right] L - \left[ \beta_{01}(\omega) - \beta_{11}(\omega) \right] L$$
$$= \left[ \beta_{01}(\omega + \Delta \omega) - \beta_{01}(\omega) \right] / \Delta \omega - \left[ \beta_{11}(\omega + \Delta \omega) - \beta_{11}(\omega) \right] / \Delta \omega \right] L \Delta \omega$$

(4-7)

where $\Delta \omega$ is the angular frequency change. On the other hand, DMD given as $\Delta \tau = \tau_{11} - \tau_{01}$ is expressed as

$$\Delta \tau = \tau_{11} - \tau_{01} = -d(\beta_{01} - \beta_{11})/d\omega.$$  

(4-8)

From Eqs. (4-7) and (4-8), DMD is written as

$$\Delta \tau = -\Delta \phi / (L \Delta \omega).$$ 

(4-9)

Since the wavelength period $\Delta \lambda$ corresponds to $\Delta \phi = 2\pi$ and $\Delta \omega = -2\pi c \Delta \lambda / \lambda^2$, Eq. (4-9) is rewritten as

$$\Delta \tau = \frac{\lambda^2}{c L \Delta \lambda},$$  

(4-10)

where $c (=3\times10^8$ m/s) is light velocity in free space and $\lambda$ is the center wavelength between adjacent minima.

Figure 4-12 shows the interference spectrum of the GI-TMF with the length of 100 m cut out from one end. Wavelength dependence of the interference pattern was observed. Figure 4-13 shows the absolute DMD $|\Delta \tau|$ as a function of wavelength which was obtained from Eq. (4-10) and the result of Fig. 4-12. It is seen from Fig. 4-13 that the DMD is 0 ps/km at 1554 nm and less than 36 ps/km in the C-band.
Figure 4-11 Experimental setup of DMD measurement

Figure 4-12 Interference spectrum of GI-TMF at 100 m

Figure 4-13 Absolute DMD property as a function of wavelength
4.4 Offset-launch Characteristics for TMF

Mode division multiplexing transmission system using Few-Mode Fiber (FMF) has attracted considerable attention [52-54]. For the system, Multiple-Input-Multiple-Output digital signal processing (MIMO-DSP) is applied to recover the signals which degrade due to mode coupling. In addition, since MIMO-DSP complexity increases with an increase of differential modal group delay (DMD) of FMF, DMD management line with below several ps/km has been reported activity [54-57]. However, in the case of DMD management line, there is fear that mode coupling noise generates at the splice points. Though mode launch characteristics of multimode fiber at the splice points were reported appreciably [58, 59], that of FMF has not been reported ever. In this chapter, Two-Mode Optical Fiber is focused and mode launch characteristics for TMF is calculated by using the finite element-beam propagation method (FE-BPM) and the validity and usefulness of the present approach are shown by comparing with experimental results.
4.4.1 Simulation for Offset-launch Characteristics using FE-BPM

Offset-launch characteristic was calculated by FE-BPM [44], which is useful for complex refractive index profile analysis. Figure 4-14 shows half of a fiber cross-section, which is divided into elements. Perfect electrical conductor was set on the boundary of $y=0$ and six perfectly matched layers were set at the outer layer. The number of node and element were 7685, 3765, respectively. Measured refractive index profile data by RNFP were given to each element and the index profile was supposed longitudinally constant. Next, Gaussian field data with offset value was set into the suitable node field data. After that, propagated field distribution was sequentially calculated by using Crank-Nicolson method. Figure 4-15 shows the power at $x = 0$ and $x = x_m$, where the intensity of $LP_{01}$ and $LP_{11}$ modes maximize under steady state condition, as a function of propagation distance in the case of TMF.

![Figure 4-14 Element division profile](image)
Figure 4-15 LP\textsubscript{01} and LP\textsubscript{11} modes power as a function of propagated distance.

It is observed that field distribution for LP\textsubscript{11} mode is interfered with LP\textsubscript{01} mode. In addition, the power for LP\textsubscript{11} mode at \( x = x_m \) changes with a period of twice coupling length between LP\textsubscript{01} and LP\textsubscript{11} modes. When total power at \( x = x_m \) and \( x = 0 \) are defined as \( P'_{\text{total}} \) and \( P'_{01} \) under steady state condition, the power for LP\textsubscript{11} mode, \( P'_{11} \) at \( x = x_m \) is represented by following equation,

\[
P'_{11} = P'_{\text{total}} - N_{xm} \cdot P'_{01}
\]  

(4-11)

Here, \( N_{xm} \) is the ratio of the power at \( x = x_m \) to \( P'_{01} \) for LP\textsubscript{01} mode. Consequently, the ratio of the power for LP\textsubscript{11} mode to total power can be approximately represented by following equation

\[
\eta_{11} \approx 10 \log \left[ \frac{P'_{11}}{P'_{01} + P'_{11}} \right]
\]  

(4-12)
4.4.2 Fiber Sample and Experimental Setup

In order to examine the validity for mode launch evaluation by using FE-BPM, the power ratio of LP_{01} and LP_{11} modes for TMF under offset-launch condition were measured. Table 4-3 shows optical properties of TMF and SMF, which was used as mode launch fiber, at the wavelength of 1550 nm.

Table 4-3 Properties of test fibers

<table>
<thead>
<tr>
<th></th>
<th>SMF-1</th>
<th>SMF-2</th>
<th>SMF-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode field diameter(MFD)(µm)</td>
<td>LP_{01}</td>
<td>6.9</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>LP_{11}</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Effective area (µm²)</td>
<td>LP_{01}</td>
<td>36.9</td>
<td>84.4</td>
</tr>
<tr>
<td></td>
<td>LP_{11}</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Δβ (rad/m)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2πΔβ (µm)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

λ=1550nm *Calculated

The properties of LP_{11} mode and Δ β were estimated value by using RNFP. Two kinds of SMF which have different mode field diameter (MFD) were used in order to examine the dependence on MFD of launch fiber. The TMF and SMF were based on a step index profile. Figure 4-16 shows calculated field distribution of TMF for LP_{01} and LP_{11} modes at the wavelength of 1550 nm.

Since the peak of field distribution for LP_{11} mode is about x = 4 µm, x_m is determined 4 µm. In addition, Nxm for LP_{01} mode of 0.49 was obtained from Fig. 4-16. Figure 4-17 shows the experimental setup for mode launch measurement. 1550-nm LD was used as light source, and offset value between TMF and SMF was controlled by fusion splicer with micro motion adjustment. Additionally, large bend, R_1 was added to remove leaky mode. When the power under this condition is defined
GI-TMF with Low DMD, Large $A_{\text{eff}}$ and Low Bending Loss

as PA, PA is represented by following equation.

$$P_A = P_{01} + P_{11} \quad (4-13)$$

where $P_{01}$ and $P_{11}$ were the power of LP$_{01}$ and LP$_{11}$ modes, respectively. Next, the power with the other bend, $R_2$ which was attenuated only LP$_{11}$ mode is defined as PB. Since PB equals $P_{01}$, $P_{11}$ is represented by following equation

$$\eta_{11} = 10 \log \left[ \frac{P_B}{P_A} \right] \quad (4-14)$$

Therefore, the ratio of LP$_{01}$ and LP$_{11}$ modes power to total power, $\eta_{01}$ and $\eta_{11}$ are represented by following equation

$$\eta_{01} = 10 \log \left[ \frac{P_B}{P_A} \right] \quad (4-15)$$

$$\eta_{11} = 10 \log \left[ \frac{P_A - P_B}{P_A} \right] \quad (4-16)$$
Figure 4-16 Calculated field distribution of TMF for LP_{01} and LP_{11} modes

Figure 4-17 Experimental setup for mode launching measurement
4.4.3 Results and Discussion

Calculated parameters were determined following; 1) wavelength \( \lambda = 1550 \text{ nm} \), 2) offset value \( d = 0, 2, 4, \) and \( 10 \mu\text{m} \), 3) MFD of incident light (with Gaussian field) \( 2W = 6.9 \) and \( 10.4 \mu\text{m} \), 4) propagation step size \( \Delta z = 8 \mu\text{m} \). BPM calculation was continued until \( \eta_{11} \) converged. The power change for LP\(_{11}\) mode of the similar tendency shown in Fig. 4-15 was obtained at all offset values, and the period of the power change was about 660 \( \mu\text{m} \), which value was in good agreement with twice coupling length (333 \( \mu\text{m} \)) calculated by RNFP. This result also means expressly that the power for LP\(_{11}\) mode is included at \( x = 4 \mu\text{m} \) in calculated field distribution.

Figure 4-18 shows the calculated \( \eta_{11} \) as a function of propagation distance at the various offset values. It is confirmed that both results of \( \eta_{11} \) converged over the distance of 3-4 mm. An offset value which is given \( \eta_{11} \) to 3 dB, that is equivalent excitation between LP\(_{01}\) and LP\(_{11}\) modes, is about 2-4 \( \mu\text{m} \) regardless of MFD of incident light and it is understood that the offset value correspond to an area where overlap between each field distribution maximizes. In addition, at the offset value from 0 to 2 \( \mu\text{m} \), change ratio of \( \eta_{11} \) was large. It means that LP\(_{11}\) mode may be launched easily even imperceptible offset value.

Figure 4-19 shows comparison results for mode launch characteristics between calculated and measured values. Solid and dashed lines were calculated values, circle and triangular point were measured values. The calculated values have the compatible properties with the measured values so that it is clarified that our approach can estimate mode launch characteristics. When the same field distribution of LP\(_{01}\) mode of TMF is input to TMF without offset entirely, LP\(_{11}\) mode is not generated theoretically (\( \eta_{11} \rightarrow - \infty \)). However, it is considered from Fig. 4-19 that when offset value is within 1 \( \mu\text{m} \), mode
coupling noise (generated LP_{11} mode) of more than -20 dB at the splice point may be generated.

Figure 4-18: Calculated value of $\eta_{11}$ as a function of propagation distance at various offset values

(a) SMF-1 ($2W = 6.9 \ \mu m$) (b) SMF-2 ($2W = 10.4 \ \mu m$)
Figure 4-19 Relationship between the offset value and the excitation ratio $\eta_{11}$
4.5 Conclusions

The optimum fiber design of GI-TMF with a low DMD, large effective area $A_{eff}$, and low bending loss for LP$_{11}$ mode has been investigated. The suitable fiber parameters for the GI-TMF has been clarified to be of $\Delta = 0.36\%$ and $\alpha = 2.3$ from the area satisfying requirements that are DMD = 0 ps/km, $A_{eff}$ of more than 150 $\mu$m$^2$ and bending loss for LP$_{11}$ mode of less than 0.01 dB/km at the wavelength of 1550 nm. The GI-TMF with $\Delta = 0.363\%$ and $\alpha = 2.29$ according to our fiber design was successfully fabricated. It has been confirmed experimentally that the fabricated GI-TMF had a large effective area $A_{eff}$ of 150 $\mu$m$^2$ for LP$_{01}$ mode, and approximately 0.016 dB/km bending loss for LP$_{11}$ mode at R = 40 mm and realized the DMD of less than 36 ps/km including zero in the C-band. It is expected that our design GI-TMF is suitable for MDM and has a potential to reduce MIMO-DSP complexity.

The mode coupling of TMF at the splice points has also been investigated by using the finite element-beam propagation method. It has been clarified that mode coupling noise of more than -20 dB at the splice points may be generated when the offset value is within 1 $\mu$m.
Chapter 5

Summaries and Conclusions

This chapter summarizes the results and achievements of this thesis. The main object of this thesis is to develop innovative optical fibers for future ultra large capacity transmission systems that overcome the capacity limit of the conventional single-mode fiber 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 have been realized. The author focused on two ways to realize the novel optical fiber that overcome those challenges. As for one way, a new optical fiber has been developed for the optical wiring utilizing the different mechanism to confine light in the core, which is PCF. As for the other way, few mode optical fiber that has the low DMD and the low bending loss has been designed and fabricated.

Chapter 2 proposed the PCFs as the novel optical fibers that overcome the tradeoff between the large effective area and the cutoff wavelength or the bending loss of the conventional single-mode fiber utilizing refractive index difference between core and cladding for
confinement of light. Before this study, PCFs had relatively high optical attenuation and the fiber length was limited to a few kilometers compared with that of a conventional single-mode fiber because of the complicated manufacturing process. Therefore, PCFs were considered to be used for the only special purpose and they were not widely deployed as transmission media. A low loss PCF design to reduce the confinement loss and the fabrication technology for fabricating the long length of PCF was proposed, and the PCF with a loss of 0.37 dB/km at 1.55\(\mu\)m and the fiber length of 10km has been realized. The possibility of reducing optical attenuation of PCF has been also shown by several trials for reducing the OH absorption. With these results, the following work realized a 100 km-long PCF with a loss of 0.3 dB/km at 1.55\(\mu\)m. A dense wavelength division multiplexing (DWDM) transmission experiment has been also shown by using the fabricated PCF.

Chapter 3 proposed a HAPCF with good bending performance for the optical wiring because the 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 the 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 loss by both conventional fusion splice and mechanical splice methods to HAPCF were no more than 0.5 dB. Based on the above results, indoor optical fiber cord with the HAPCF was specified in NTT and had been deployed in indoor optical wiring applications in many countries.

Chapter 4 proposed an optimized GI-TMF as a new multimode optical fiber that has low DMD and low bending loss. It has been clarified the suitable fiber parameters for the GI-TMF satisfying requirements that are DMD = 0 ps/km, \(A_{\text{eff}}\) of more than 150 \(\mu\)m\(^2\) 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 an 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 evaluation of mode coupling of TMF at the splice point has been also proposed 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 our design of GI-TMF is suitable for MDM and has a potential to reduce MIMO-DSP complexity.

The author had been related to R&D of optical fibers for more than 30 years since the initial deployment of optical fibers to the telecommunication network in Japan. Research for innovative optical fibers for ultra large capacity transmission systems that will overcome the capacity limit imposed by the combination of Shannon-Hartley theorem and nonlinear fiber effects had started utilizing the knowledge and experience of actual deployment. This study clarified that novel optical fibers that overcome the limiting factors of conventional single-mode fibers will be able to contribute to realize the ultra large capacity transmission systems to accommodate dramatically increasing traffic.
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Table 4-3 Properties of test fibers
List of Acronyms

$A_{\text{eff}}$: effective area
BER: bit-error rate
DAC: dual shape core
DCF: dispersion compensating fiber
DMD: differential modal group delay
DSF: dispersion-shift fiber
DSP: digital signal processing
DWDM: dense wavelength division multiplexing
FE-BPM: finite element-beam propagation method
FEM: finite element method
FMF: few-mode fiber
FTM: fiber termination module
FTTH: fiber to the home
GI: graded index
HAPCF: hole assisted type PCF
IDM: integrated distribution module
IGPCF: index guiding type PCF
INS: information network system
LD: laser diode
LED: light emitting diode
LP: linear polarisation
MDM: mode division multiplexing
MFD: mode field diameter
MIMO: multi-input multi-output
MMF: multimode fiber
NRZ: non return-to-zero
NTT: Nippon Telegraph and Telephone Public Corporation
    Nippon Telegraph and Telephone Corporation from 1985
ONU: optical network unit
OTDR: optical time domain reflectometry
PBGF: photonic band-gap type PCF
PCF: photonic crystal fiber
PM: power meter
R&D: research and development
RNFP: refractive near field pattern
SDH: synchronous digital hierarchy
SMF: single-mode fiber
SNR: signal to noise ratio
TIR: total internal reflection
TMF: two mode fiber
VAD: vapor phase axial deposition
VI&P: visual, intelligent & personal
WDM: wave division multiplexing