Hollow Core Fiber Cable

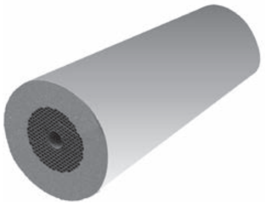
*Kazunori Mukasa**

ABSTRACT Hollow core fibers (HCF) are innovative optical fibers having the potential to break the limits of conventional optical fibers. Examples of innovation are ultra-low loss potential, ultra-low nonlinearity, and long interaction lengths with gases confined to the core. In addition, ultra-low latency characteristics have attracted much attention in recent years, particularly amongst financial trading communication systems. For the first time in the world, we have succeeded in developing a high-performance HCF with practical single mode (SM) properties achieved by a resonant couple phenomenon, to implement the HCF in the low latency transmission. Furthermore, we have successfully developed HCF connectors and HCF cables to achieve the actual low latency transmission. These development results are reported.

1. INTRODUCTION

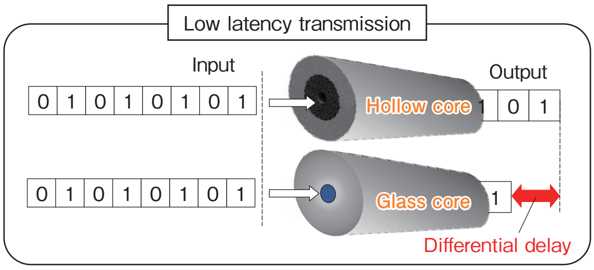
The confinement of light in HCF is different from the conventional mechanism of total internal reflection (TIR) which relies on a high index core surrounded by a low index cladding. On the other hand, since HCF can propagate 99% or more light in the hollow core with a refractive index of approximately 1.0 by the photonic bandgap (PBG) or the anti-resonant principle, then the effective group index of light becomes about 1.002~1.003. This is significantly lower than the 1.47 obtained with conventional glass fibers, and other various characteristics that are difficult to achieve with the conventional glass core fiber are possible to achieve.[1)-3)] Confining and guiding light in an air core which has a low refractive index enabled novel properties that are difficult to achieve in conventional optical fibers, such as low latency, low nonlinearity while maintaining low bending loss characteristics as summarized in Figure 1.

Among these, the ultra-low latency characteristics are attracting attention for applications such as in the high-speed trading in the financial services, the high-speed computing, Beyond 5G, various remote controls, and wiring in data centers.[4), 5)] Even with the glass fiber, for example, by using a pure silica core and a depressed type cladding a certain improvement is possible, but its improvement rate is small about few percent at best. Whereas, by changing the core from glass to the hollow core, 30% or more of significant improvement is possible in the latency characteristics. The improvement becomes more remarkable as the link length becomes longer. Figure 2 shows the improvement rate, with length, of the latency in HCF. The improvement on the order of a microsecond is obtained for link lengths exceeding 1 km. It can



Unique principal of the hollow core fiber	Innovative characteristics
Light is confined not in the glass core but in the air core	Ultra-low latency characteristics
	Ultra-low loss potential
	Ultra-low nonlinearity
	Super high reliability / Resistance feature to severe environment
	Interaction with a gas in the core
Light confinement is based on a principle different from the conventional total internal reflection mechanism	Ultimate low bending loss characteristics
	Unique dispersion / polarization characteristics

Figure 1 Examples of innovative characteristics achieved by HCF.



Link length	Glass core latency time	Hollow core latency time	Improvement of latency
300 m	1.47 μs	1.00 μs	0.46 μs
500 m	2.44 μs	1.67 μs	0.77 μs
1,000 m	4.89 μs	3.34 μs	1.54 μs
10,000 m	48.9 μs	33.4 μs	15.4 μs

Figure 2 Improvement rate of the latency characteristics in HCF.

---

* R & D Division, Telecommunications & Energy Laboratories

be said that the transmission line with HCF has potentially extremely high needs, since it is considered to be an important characteristics not only in niche fields such as financial transactions, but also in fields such as autonomous-driving, remote medical services and factory operations where transmission latency can be fatal in the future6), 7).

However, not only the innovations but also many issues which are necessary to be solved exist in HCF for its practical applications. For example, though theoretical predictions indicate ultra-low loss potential, the loss of the current HCF is higher compared to that of the conventional silica fiber. Further investigation is necessary to reduce the loss of HCF by optimizing the processes. In addition, it is a significant problem that multi modes (MM) propagetes in HCFs, which is highly undesirable, as SM transmissions are expected to become the standard in many low-latency transmission routes. There are several types of HCF such as the photonic bandgap fiber (PBGF) and the anti-resonant fiber (ARF). PBGF has been investigated for the longest time, and we also have been studying with PBGF type. PBGF has a regular array structure formed in its cladding in order to prohibit wavelength groups and angle groups of light from propagating within the cladding by the photonic bandgap (PBG) phenomenon. By forming an irregular structure (defects in structure) in the central part, launched light into the hollow core is prohibited from propagating in the cladding due to PBG phenomenon and a mode is formed in the core and propagates. The dominant factor of the loss is scattering loss which is induced at the rough interface (frozen-in capillary wave) between air and glass created by heat during the fabrication process.2) PBGF is classified into 3-cell type, 7-cell type, 19-cell type, etc. depending on how many times sizes of the core are larger compared to the size of regular structures in the cladding. The larger core has a smaller intensity of light that overlaps with the glass surface, and the transmission loss tends to decrease. On the other hand, the larger the core, the more the High Order Modes (HOMs) are confined, and it allows the propagation of more modes.8) This is a major obstacle in applying PBGF to the low latency transmissions that use existing transmitters and receivers. For the actual use of HCF in low latency transmission, the establishment of peripheral technologies, such as connection and cable fabrication, is also necessary, but very little investigation has been made on those technologies. As described above, though the potential of HCF is very high, there are many issues that need to be overcome for the practical use of HCF in low latency transmission.

2. DEVELOPMENT OF A NEW HOLLOW CORE FIBER HAVING AN EFFECTIVE SM-PROPERTY (PRISM-PBGF)

As described, in PBGF, achieving both low loss and SM operation are a key issue for its application in the actual transmission. To achieve these desirable properties, we applied a new structure that is different from the conventional structure. With the new structure, it became possible to suppress the propagation of HOMs while maintaining the core of 19-cell.9)-11) A Scanning Electron Microscopy (SEM) of the structure is shown in Figure 3. The most notable feature of this fiber is that it uses a 19-cell type core which can achieve a low transmission loss, but has a special structure called Perturbed Resonance for Increased Single Modedness (PRISM) structure, which has two cores next to the center core (Shunt cores) corresponding to 7 cells. With this structure, the HOMs in the center core are selectively coupled to the shunt cores to suppress its propagation, and this achieves an effective SM transmission. By matching the effective group index of the HOMs with the effective group index of the fundamental mode of the cores, the HOM of the light signal in the center core is coupled with the shunt cores at high efficiency. Since the shunt cores are located near the edges of the cladding of the light, the coupled light leaks out efficiently without propagating through the shunt cores. By this newly developed structure that applies this unique principle, preferable properties of low loss and effective SM that were not possible with the conventional PBGFs can be achieved. This concept is important and novel that would get rid of the major obstacles in the practical application of HCF.

A very advanced technology is required for the fabrication of the PRISM type PBGF.

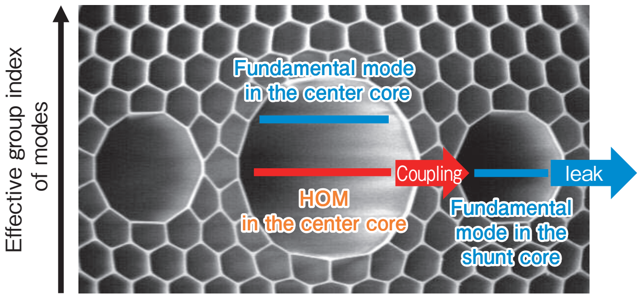


Figure 3 SEM image of the newly developed PBGF.

Figure 4 shows an example of a fabrication process. A large number of thin glass capillaries are put (stacked) into a silica jacket tube and a fiber is drawn while maintaining a regular arrangement. At first, a regular hexagonal close packed structure is assembled in a jacket tube without the distortions of the structure to obtain the basic structure. This is an important process for obtaining the required properties in PBGF. Not only the regularity of the cladding but also the appropriate position and structure of the center core and the shunt cores are necessary, and a very advanced processing technology is required. The drawing process is also a key process in order to achieve PBGF with good characteristics. The assembled capillaries and tubes need to be drawn to obtain the optical fiber, while collapsing the interstitial holes between the capillaries and the tubes without any significant distortion to the overall structure.

We have established the advanced process technologies and successfully achieved a PBGF with very regular structures and desirable optical characteristics over a long length of fiber. Figure 5 shows an example of the cross-sectional structure and transmission loss.

As described above, the most significant feature of the HCF presented here is that the loss of the HOM is suppressed by the PRISM structure. Figure 6 shows the field distribution of a typical 19-cell HCF and the PRISM fibers

Figure 4 **Concept diagram of the newly developed PBGF processes.**

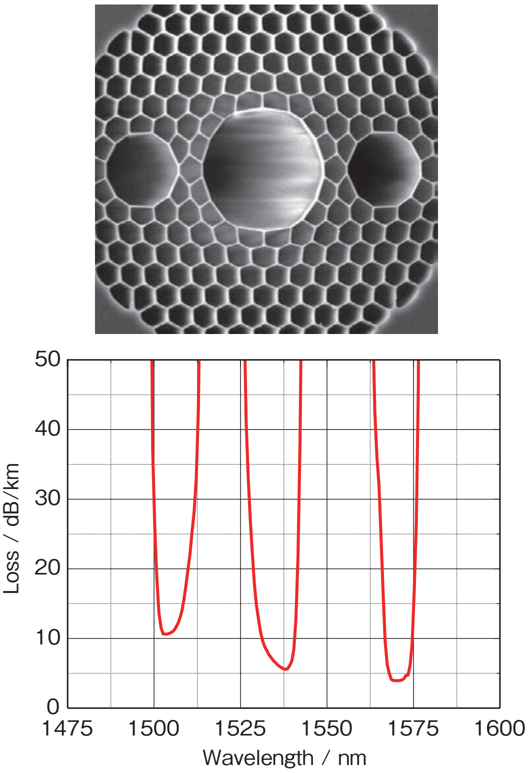


Figure 5 **Structure and loss spectrum of the newly developed PBGF.**

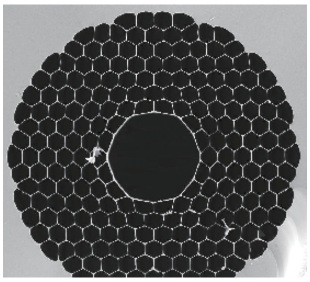
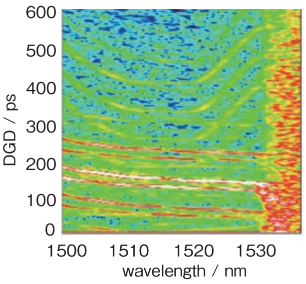
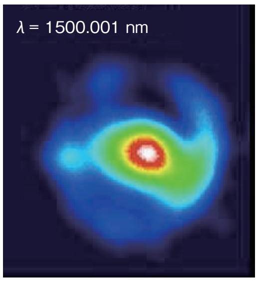
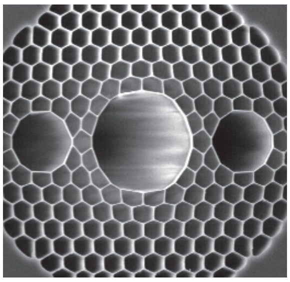
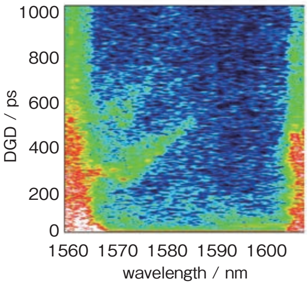
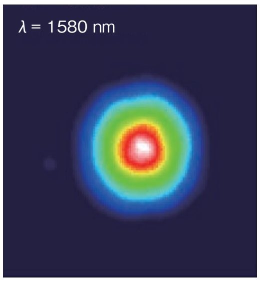
	Cross sectional images	Example of a HOM characteristics spectrum and a field distribution	
Conventional type 19-cell PBGF			
PRISM structure 19-cell PBGF			

Figure 6 **Examples of traditional and the newly developed PBGF mode profiles and spectrograms.**

along with the spectrogram11) of the PRISM fibers. The blue darker areas correspond to the area where the propagation of HOM is suppressed and the red and green areas correspond to an area with HOM components. As Figure 6 shows, effective SM operation, which was difficult to achieve with the conventional 19-cell PBGF, can be achieved by effectively coupling HOM to the shunt cores in a PRISM fiber. Field distributions of the PRISM fiber also represent a more Gaussian-like field distribution, typically associated with a fundamental mode of an SMF. Thus, it was confirmed that the newly developed PRISM type PBGF has characteristics more suitable for a practical use.

In order to suppress further higher order modes, PBGFs with 6 shunt cores were developed, as shown in Figure 7.12) The concept is the same, but effective SM performance can be ensured more reliably, as the problem of a coupling efficiency reduction caused by a bending direction is suppressed by shunt cores that couple HOM at six places. As shown in Figure 7, by increasing number of shunt cores from 2 to 6, no deterioration in the transmission loss of PBGF was observed.

Figure 8 shows HOM characteristics of 2-shunt core type and 6-shunt core type fibers (5 m in length) wound on a 15 cm of coil. As is clear from Figure 8, even with the 2-shunt core type, the effective SM characteristics have been obtained, but by adopting the 6-shunt core type, HOM component in the transmission band is further suppressed. So, it can be seen that achievement of low transmission loss characteristics and further improvement of SM performance, which are important for the actual transmission, are achieved.

When installing HCF cable in the actual field, the HCF has to be robust and withstand environmental conditions such as sunlight, hot and cold temperatures and mechanical vibration. The 6-shunt core type PBGF with further stable mode characteristics was used for the trial cable fabrication described later. The characteristics of the two PBGFs used in the trial cable fabrication are shown in Figure 9. Not only in the spool state but also after the cable fabrication, the loss increase was small and stable low loss characteristics were obtained. Also, the dispersion characteristics of all the fibers used in the trial cable fabrication were controlled to low values at 1550 nm, which were preferable characteristics for low-latency transmission.

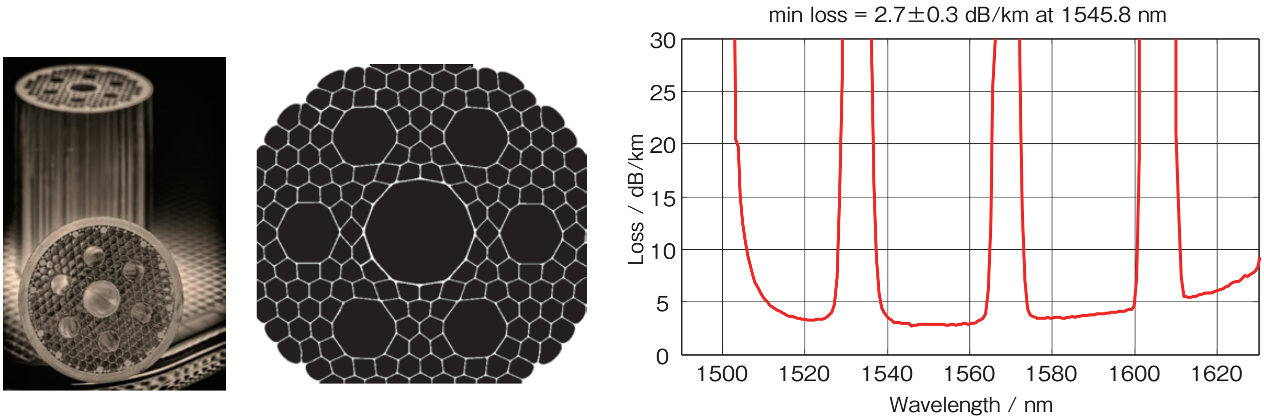


Figure 7 Stacked preform and SEM of the fiber for 6-shunt core type PBGF (left) and its transmission loss (right).

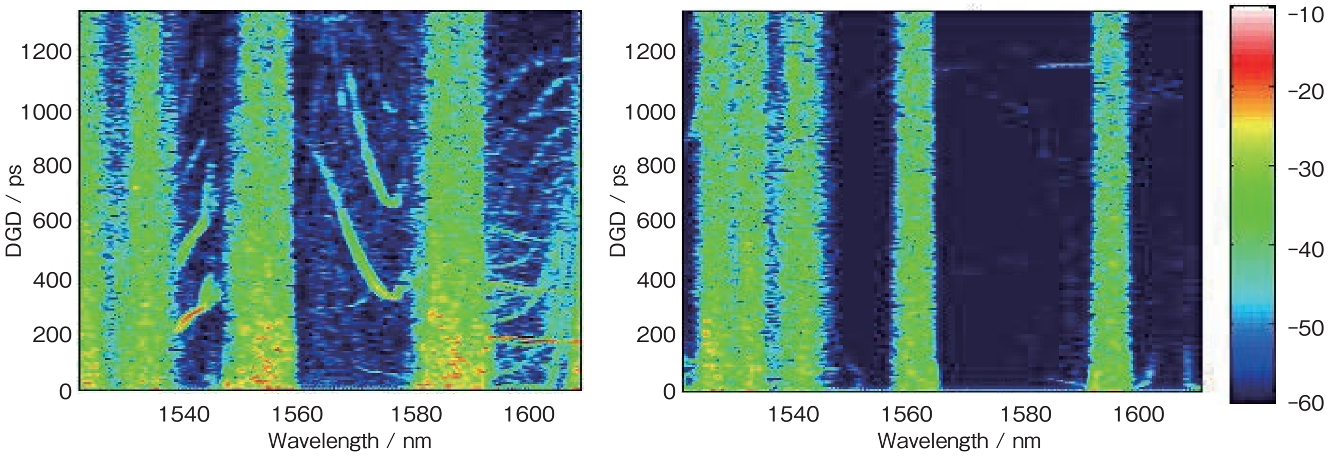


Figure 8 Mode spectrograms of 2-shunt core (left) and 6-shunt core (right) PBGFs.

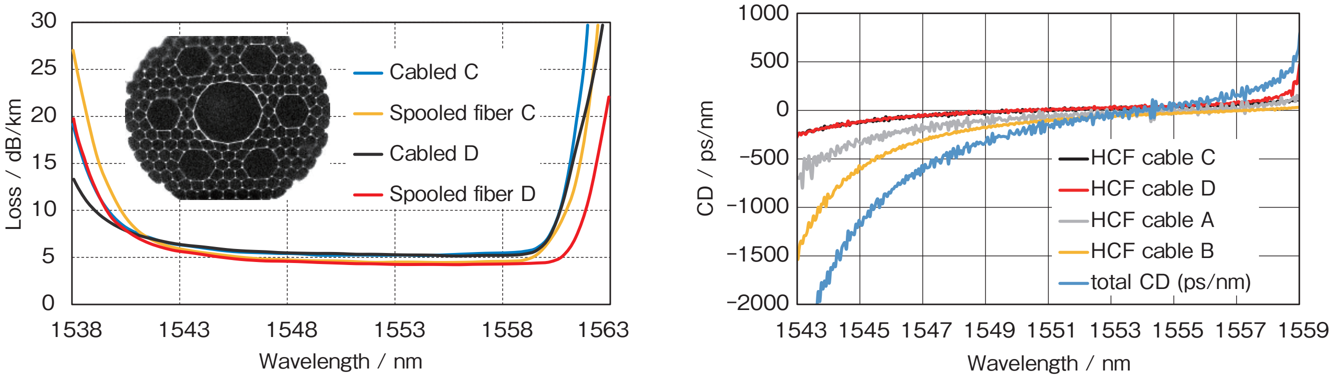


Figure 9 Examples of structure and loss of 6-shunt core PBGF and wavelength dispersion characteristics.

3. DEVELOPMENT OF THE RELATED TECHNOLOGIES FOR PRACTICAL USE

3.1 Development of PBGF Connectors

For the practical application of HCF, connection technology is an important factor. Fusion splicing and a connector can be considered as important connection technologies. For the fusion splicing, various investigations have been carried out13)-15), but there was a problem that the fusion splicing loss was high because of the significant mode field mismatch between HCF and the conventional SMF and deformation of the PBGF structure by splicing. Also, reflection loss tended to be high. With the cable using PBGF, we have since lowered splice losses to the order of 1 dB. The PBGF connector is a key component for ease of installation into existing transmission systems, but the realization has been difficult. We have succeeded in the development of PBGF connector for the first time in the world16). For the connector, we used PRISM type PBGF which is our original structure. Since the 19-cell core structure is used for the center core, in spite of low transmission loss of 3.9 ±1.2 dB/km (1571 nm), the effective SM performance is achieved. An effective core area (Aeff) of this PBGF is 200 μm^2, which is much larger compared to the 80 μm^2 of conventional fibers. Therefore, a coupling loss is expected to be large when connecting this connector with SMF due to the difference in Aeff. Then, the coupling loss caused by a physical bonding between PBGF and solid fibers having different Aeff values prepared by flat cleave, was investigated. The results are shown on the left side of Figure 10, and it can be seen that when Aeff of the solid fiber is about 165 μm^2, the coupling loss is minimized to about 0.25 dB. This is close to the theoretical limit, considering the coupling of a solid fiber with a circular Gaussian mode and PBGF with a more hexagonal field. Based on this result, we fabricated an FC/PC connector using a solid fiber with Aeff of 165 μm^2. In order to suppress the reflection loss, Anti-Reflection (AR) coating was applied for this time. The right side of Figure 10 shows the reflection loss of the flat cleaved fiber and the AR coated connector, and it is found that the reflection loss at 1585 nm can be reduced to −42.5 dB by the AR coating.

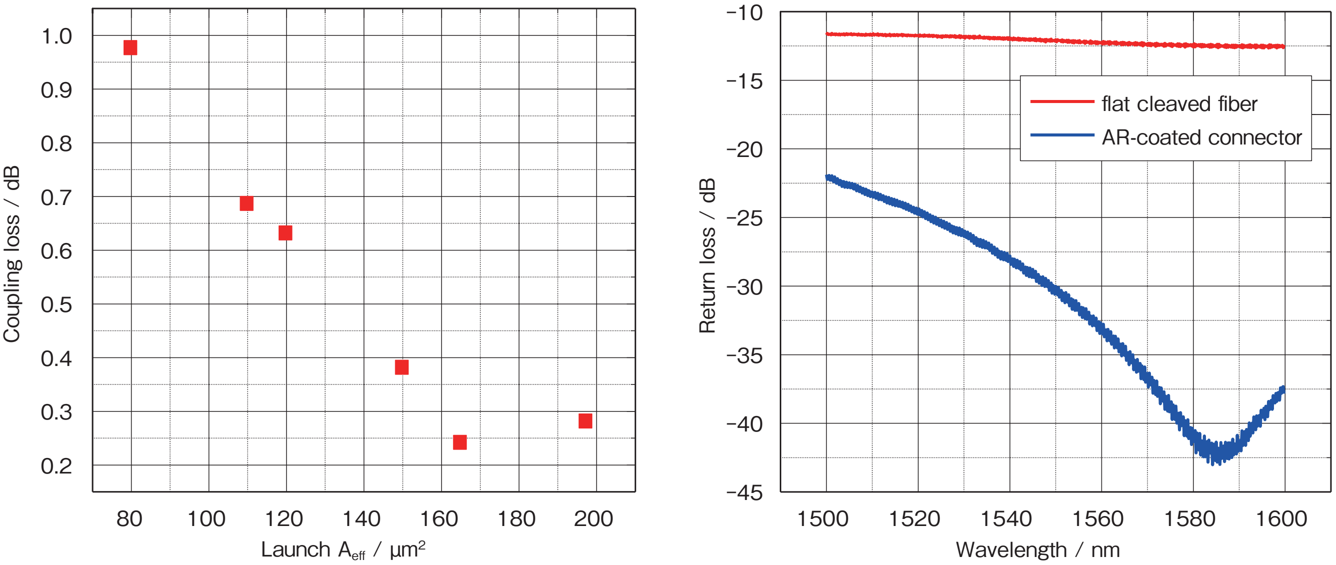


Figure 10 Coupling loss and connector reflection loss characteristics by physical coupling between PBGF and solid fiber.

Regarding the HCF connector, HCF was inserted into the central void part of the FC/PC connector as shown in Figure 11, the protruding part was flat cleaved, and the fiber end surface was pulled back to the surface of the connector and fixed with epoxy resin. The fabricated HCF connector was joined with the aforementioned AR coated enlarged-Aeff solid fiber connector. The right side of Figure 11 shows the obtained optical properties. The insertion loss of a jumper cable which consists of two connectors was 1.4 dB at 1571 nm, which was only 0.6 dB higher than the loss of the fiber itself. The difference in the insertion loss from the incident direction was hardly observed. And, the reflection loss at 1571 nm was very low at −31.3 dB by using the AR coating, but further improvement is possible by adjusting the transmission window of the PBGF to match with the effective wavelength of the AR coating.

The coupling loss from the AR coated Aeff enlarged fiber connector to the HCF connector was approximately 0.3 dB, which is slightly higher than the 0.25 dB for physical contact bonding, but the loss obtained by the fusion splice optimization was approximately 0.75 dB, and which shows a clear advantage. It is also a dramatic improvement compared to the 1.2 dB[11)], which is a record of angle-cleaved physical contact losses between 7-cell PBGF and SMF. Therefore, the developed technology on the HCF connector would be a key for the practical application of HCF.

3.2 Development of PBGF Cables

It is well known that the optical properties of an optical fiber can be changed such as due to tensile strain during the cable fabrication process, or an environment effect after cable fabrication. Similar with conventional fibers, it is necessary for HCF to evaluate characteristics such as loss, dispersion and polarization mode dispersion (PMD) in the conditions in which the cable is actually used. Using the PBGF with 6-shunt cores, as described in section 2, the world's first loose tube type PBGF cable was fabricated and evaluated.[17)] Each cable was terminated with an LC/UPC connectors that were fusion spliced to SMFs. The increase in loss after cabling was less than 0.7 dB/km at wavelengths between 1544.9 and 1558.6 nm, and no significant transmission penalty has been observed in the severe environmental tests at −40°C to 80°C of temperature. PMD characteristics are important optical characteristics in PBGF the same as with the conventional fibers. Figure 12 shows the PMD of PBGF drawn without twisting (left) and the PMD of the PBGF drawn with twisting (right). The fiber drawn without twisting was measured in a spool state (orange) and in a cable

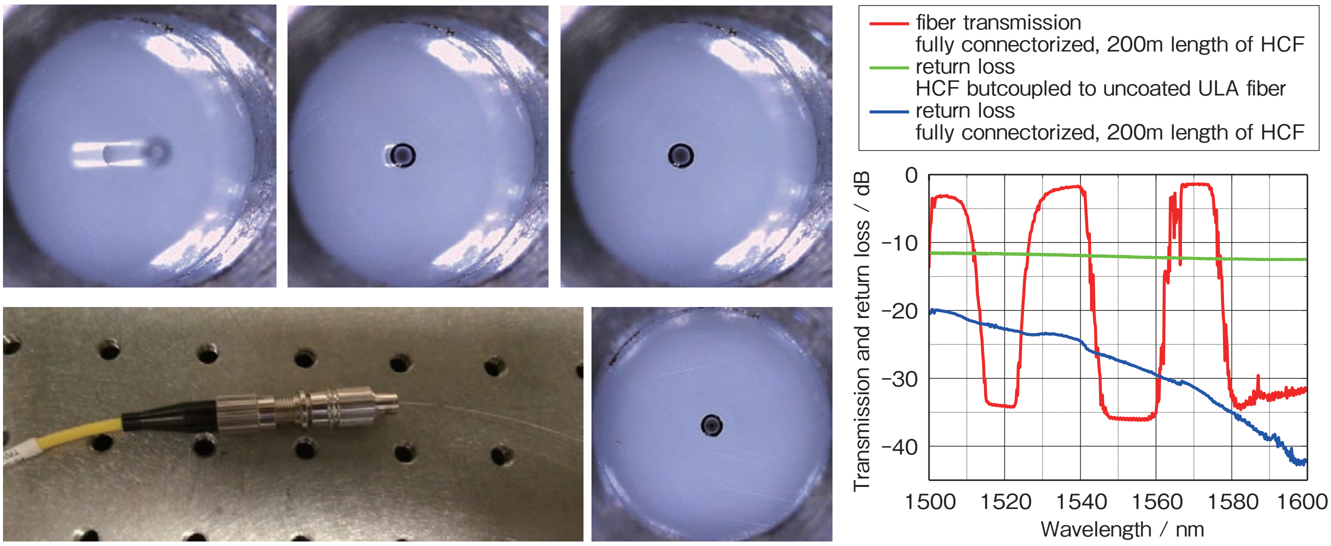


Figure 11 Images (left) and characteristics (right) of PBGF connectors.

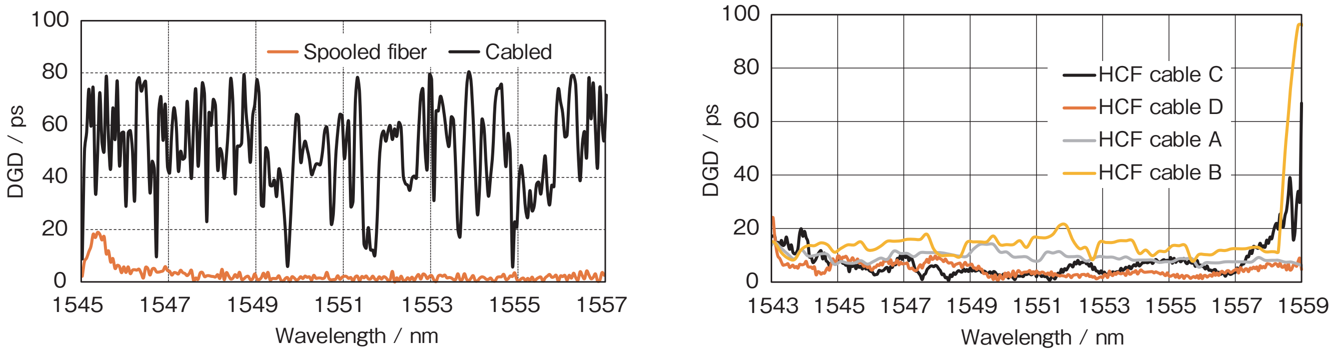


Figure 12 PMD characteristics of the fiber without twisting (left) and the fiber with twisting in cables (right).

state (black). In a spool state, the PMD reduction effect was observed due to the coupling of polarized light caused by overlapping of the fibers, but after being cabled the effect was reduced and appeared the PMD that the fibers had intrinsically. As shown in the right side of Figure 12, we successfully reduced PMD even after cabling, by the effect of polarization coupling which is caused by continuous twisting when drawing at a pitch longer than the beat length of the fiber. The typical PMD in 1 km of length was less than 10 ps.

In order to evaluate the performance of the fabricated HCF cable, 10Gb/s non-return-to-zero (NRZ) signal WDM transmission experiment was carried out. 35 signal light channels with wavelengths from 1544.92 nm to 1558.58 nm were multiplexed at 50 GHz spacing by separating the odd-numbered channels and even-numbered channels, and incident on HCF. A booster amplifier was applied at the input side of the transmission link which consisted of two 0.59 km length HCF cables and two 1 km length HCF cables, approximately 3.1 km in total, each fiber is terminated with LC/UPC connectors fusion spliced with conventional SMFs.

This time, since the configuration includes fusion splices, the total link loss at 1550 nm was 30 dB, but further reduction would be possible by using the above-described PBGF / large Aeff fiber connector. The transmitted signal was amplified, demultiplexed, and sent to the receiver, where the Bit Error Rate (BER) was measured.

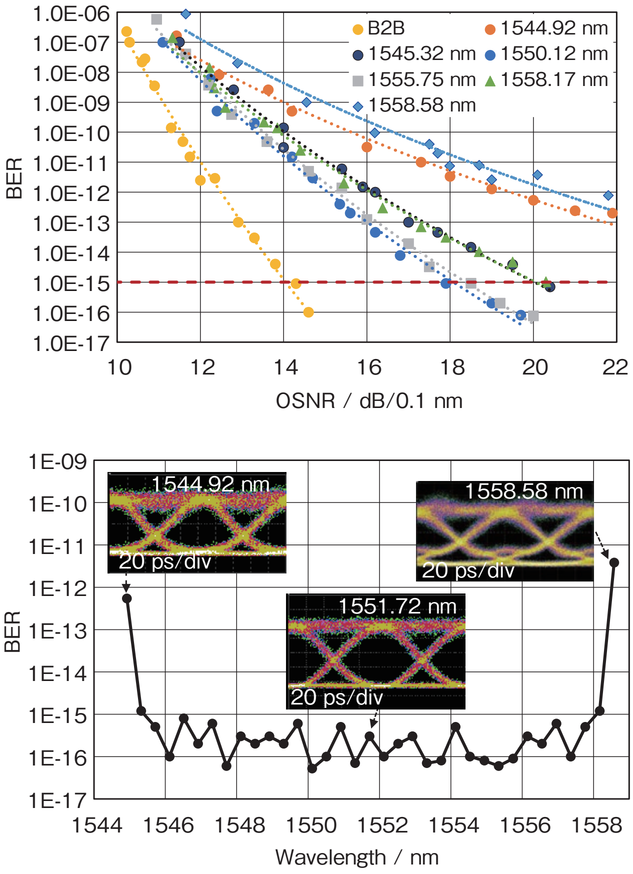


Figure 13 Transmission characteristics of HCF.

The obtained characteristics are shown in Figure 13. The upper side of Figure 13 shows the relationship between the Optical Signal to Noise Ratio (OSNR) and BER for the signals at 2 wavelengths near the center of 35 channels in the wavelength range from 1544.92 nm to 1558.58 nm, and the signals at 4 wavelengths near the edges. BER of less than 10^{-15} were obtained in 33 channels in between 1545.32 to 1558.17 nm. Most of the channels have OSNR penalty of 4 to 5 dB at BER of 10^{-15}, but the channels near the edge have penalty of approximately 6 dB. On the lower side of Figure 13, the BER and several eye diagrams are shown when the received OSNR is 20 dB / 0.1 nm. Error-free transmission (BER<10^{-15}) was confirmed for 33 channels, and the system margin of 4.5 dB / 0.1 nm was confirmed on average. From the eye diagrams, it was observed that short wavelength penalties are mainly caused by dispersion, and long wavelength penalties are mainly caused by PMD. As a result, very good transmission performance was confirmed with the actual HCF cable. We believe this achievement is very important ensuring the high performances when the HCF cables will be used in many real practical applications, such as low latency transmission or supercomputing, in the future.

4. CONCLUSION

Remarkable progress has been made in the research on HCF cables, which are expected to expand into applications such as financial trading transmission. By optimizing the unique and novel PRISM structure and the fabrication process, we succeeded in achieving both a low loss and a practical SM of HCF. In addition, the HCF connector and the cable connected with LC / MC connector were successfully developed, making great strides towards its application to real low-latency transmission. The effect on PMD by cabling was investigated, and by solving the problem in the fiber drawing process, the HCF was successfully cabled with no significant degradation in the optical properties. By these optimizations, BER free transmission (BER < 10^{-15}) in 33 channels over 3.2 km of cabled HCF has been demonstrated. We believe that such comprehensive research results for practical use will lead to the actual use of HCF in low-latency transmission lines.

ACKNOWLEDGEMENT

This review paper was mostly supported by investigations by Brian J. Mangan, Jeffrey W. Nicholson, Zhu Benyuan, Tristan Kremp, Merari Cortes, Matt Corrado, Gabe Puc, Yuriy Dulashko, Vitaly Mikhailov, Robert S. Windeler, Eric M. Monberg, Kyle Dube, Ken Marceau, Brian Violette, Donald Cartsounis, Ralph Lago, Brian Savran, Tahar Irid, Robert J. Blakley, Ji Lie, Daryl Inniss, David J. DiGiovanni and other members in OFS.

REFERENCES

1) P. J. Roberts et al.: “Ultimate low loss of hollow-core photonic crystal fibres”, Opt. Express, Vol. 13, No.1, pp.236-244, (2005).
2) B. J. Mangan et al.: “Low loss (1.7dB/km) hollow core photonic bandgap fiber”, OFC 2004, paper PD24, (2004).
3) T. D. Bradley et al.: “Antiresonant hollow core fiber with 0.65dB/km attenuation across C and L telecommunication bands”, ECOC 2019 PD.3.1, (2019).
4) B. J. Mangan et al.: “First demonstration of hollow-core fiber for intra data center low-latency data transmission”, OFC 2015, paper M3D.4, (2015).
5) Y. Chen et al.: “Demonstration of an 11 km hollow core photonic bandgap fiber for broadband low-latency data transmission”, OFC2015, paper Th5A.1, (2015).
6) K. Mizushima et al.: “Evaluation of influence of delay of image information on steering maneuver in remotely controllable automated driving system”, Transactions of the Society of Automotive Engineers of Japan, Inc., Vol. 50, No. 3, pp.970-976, (2019). (in Japanese)
7) I. Maida et al.: “Influence of visual delay on minute pointing and push down by upper limb assuming telesurgery application”, Transaction of the Virtual Reality Society of Japan, Vol.22 No. 1, pp.61-69, (2017). (in Japanese)
8) M.N. Petrovich et al.: “Robust single mode hollow core photonic bandgap fiber”, Opt. Express 16, pp.4337-4346, (2008).
9) J. M. Fini: “Aircore microstructured fibers with suppressed higher-order modes”, Opt. Express 14, pp.11354-11361, (2006).
10) J. M. Fini et al.: “Low-loss hollow-core fibers with improved single-modedness”, Opt. Express, 21(5), pp.6233-6242, (2013).
11) J. W. Nicholson et al.: “Measuring higher-order modes in a low-loss, hollow-core, photonic-bandgap fiber”, Opt. Express 20, pp.20494-20505, (2012).
12) B. J. Mangan et al.: “Single mode, polarization maintaining hollow core fibre with significantly improved higher order mode reduction”, ECOC 2015, Mo.3.1.2, (2015).
13) F. Couny et al.: “Reduction of Fresnel back-reflection at splice interface between hollow core PCF and single-mode fiber”, IEEE Phot. Tech. Letter 19, pp1020-1022, (2007).
14) L. Xiao et al.: “Fusion splicing photonic crystal fibers and conventional single-mode fibers: Microhole Collapse Effect”, J. Lightwave Technology 25, pp3563-3574, (2007).
15) K. Z. Aghaie et al.: “Optimization of splice loss between photonic-bandgap fibers and conventional single-mode fibers”, Opt. Lett. 35, pp.1938-1940, (2010).
16) J. W. Nicholson et al.: “Low-loss low return-loss coupling between SMF and single-mode, hollow-core fibers using connectors”, CLEO Applications and Technology, paper JTu4A, (2014).
17) B. Zhu et al.: “First demonstration of hollow-core-fiber cable for low latency data transmission”, OFC 2020, paper Th4B.3, (2020).