Contribution to the achievement of SDGs
by Furukawa Electric Group

Studies for Practical Applications of the Hollow Core Fiber

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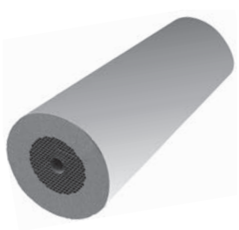
ABSTRACT The Hollow Core Fiber (HCF) has attracted the attention as an innovative optical fiber that has the potential to break through limitations of conventional optical fibers in terms of low latency, low loss, low nonlinearity, environmental resistance and so on. We have succeeded ahead of the world in achieving in making both Single Mode (SM) and low loss HCF, in connectorizing, and cabling of the HCF with our unique structure. The results of these developments were reported in Furukawa Electric Review No. 52[1]. Subsequently, we have conducted reliability tests, optimization of fusion splicing conditions, cable installation tests, and application evaluation experiments in order to further promote practical applications of the HCF. We are reporting on the results of these investigations here.

1. INTRODUCTION

Conventional optical fibers confine light to a glass core via total internal reflection, which is achieved by making the refractive index of the core higher than that of the cladding. On the other hand, The HCF can confine the light within the hollow core and propagate it using the photonic band gap principle and the anti-resonant principle, making it possible to realize characteristics that are difficult to achieve with conventional glass core fibers[2)-4)]. Innovative characteristics that can be achieved with the HCF are summarized in Figure 1. It can be understood that various characteristics that cannot be achieved with conventional glass core fibers have been realized, such as low latency, low nonlinearity, low scattering and absorption loss, etc. As fundamental limitations of conventional glass-based fibers are being increasingly seriously discussed, the HCF has attracted much attention.

Application studies that take advantage of low latency characteristics of HCF have been actively conducted[5), 6)], but in recent years, application studies that take an advantage of the ultra-low nonlinearity or high-power resistance have also been actively carried out. As one example of such applications, the application to the next-generation access is being studied. Figure 2 shows an example of the configuration, but in the future, it is thought that multi-branch Passive Optical Network (PON) systems with 256 or more branches will be applied. In addition, in the future, it is assumed that applications for not only information transmission, but also power transmission by light, for example, charging IoT devices, will increase. In considering such applications, the power input to the transmission line is expected to be orders of magnitude larger, so if the transmission is performed using conventional optical fibers, concerns arise such as degradation of signal quality due to nonlinear effects and



Unique characteristics of the HCF	Innovative characteristics
Light is confined in the air core instead of the medium core.	Ultra-low latency
	Extremely low loss potential
	Extremely low nonlinearity
	Ultra-high reliability and resistance to harsh environments
	Interference with introduced gas
Light is confined based on a principle different from the conventional theory of total reflection.	Extremely low bending loss characteristics
	Special dispersion and polarization characteristics

Figure 1 Examples of innovative characteristics achieved by the HCF.

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the glass damage due to fiber fuse. On the other hand, if a HCF with extremely low nonlinearity is used for the transmission line, these issues can be . Some examples are reported in Chapter 3.

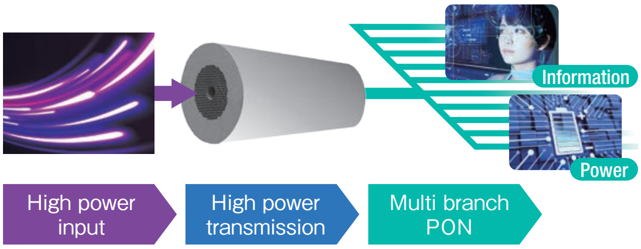

Figure 2 An example of the next generation access system using the HCF.

2. RESOLUTION OF ISSUES TOWARD PRACTICAL APLICATIONS [From Furukawa Electric Review No. 52]

As described, the HCF has a lot of innovative properties but there are many issues to be solved, for example, making it SM and the improvement of peripheral technologies. In Furukawa Electric Review No. 52[1], we reported on results of these developments, but we will briefly describe results again.

First, as far as making it SM, we succeeded in achieving both low loss and making it SM by applying to the Photonic Band Gap Fiber (PBGF) a new structure called Perturbed Resonance for Increased Single Modeness (PRISM), which is different from the conventional structure[7]. Figure 3 shows the mode spectrogram characteristics, the loss characteristics, and the structure of the new PBGF, and its good characteristics in terms of both SM characteristics and its low transmission loss can be confirmed.

In order to commercialize the HCF, the advancement of peripheral technologies such as splicing, cabling, etc., other than the fiber technologies will also be an important factor. As far as the connection technology, technologies such as a fusion splice, a mechanical connector, etc., can be thought, but we have been successful in developing the first PBGF connector in the world[8]. We also produced the first loose tube type PBGF cable in the world and confirmed their excellent characteristics[9].

Figure 4 shows the structure and characteristics of the fabricated HCF connectors. The coupling loss from the AR-coated Aeff expanded fiber connector to the HCF connector was approximately 0.3 dB, and the reflection

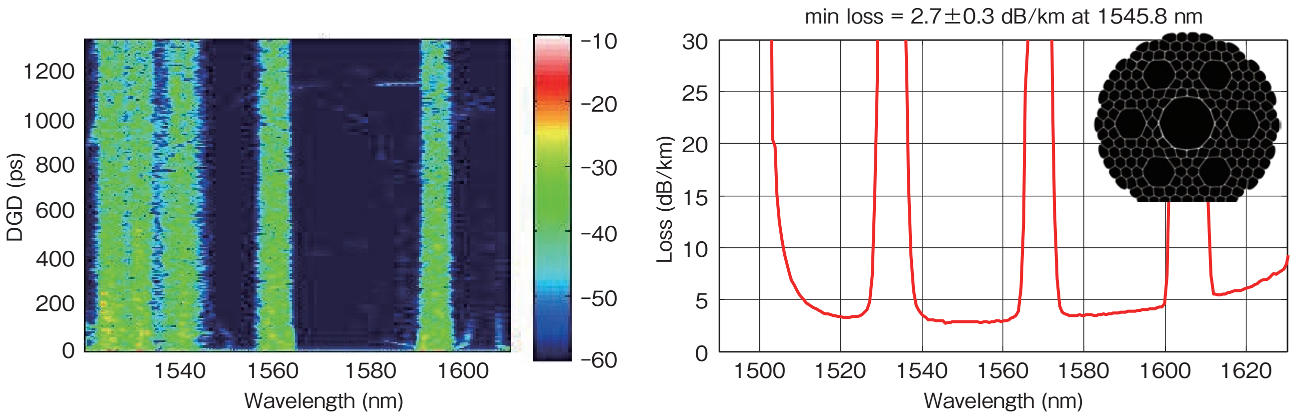

Figure 3 Mode spectrogram characteristics, transmission loss characteristics and an example of cross sectional structures for the newly developed HCF.

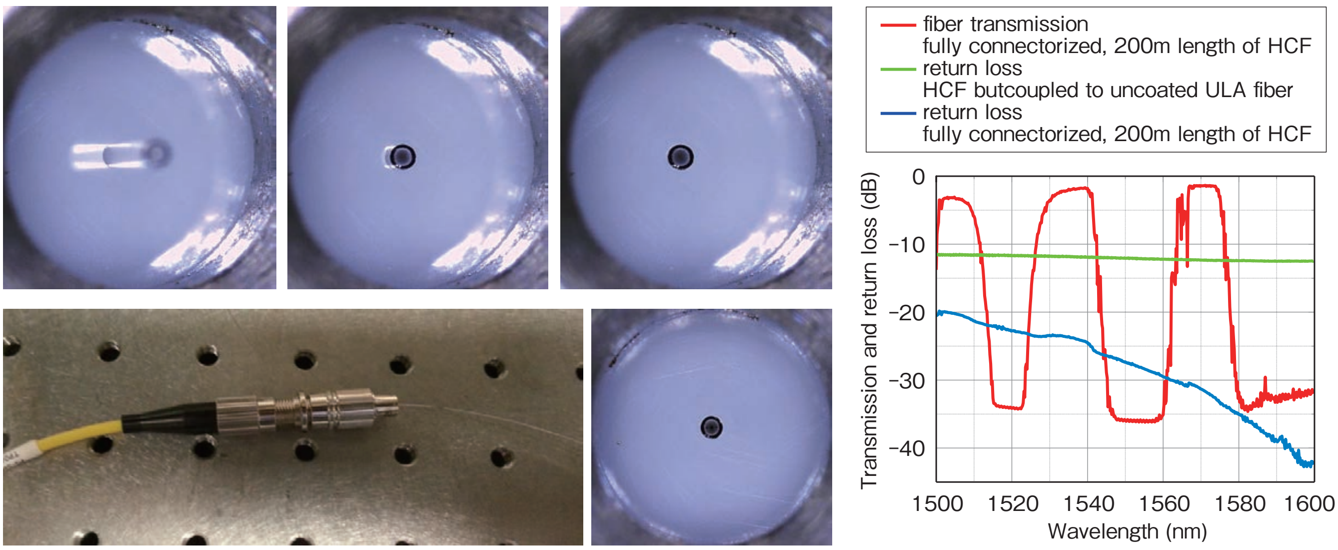

Figure 4 Pictures of PBGF connectors (left side) and their characteristics (right side).

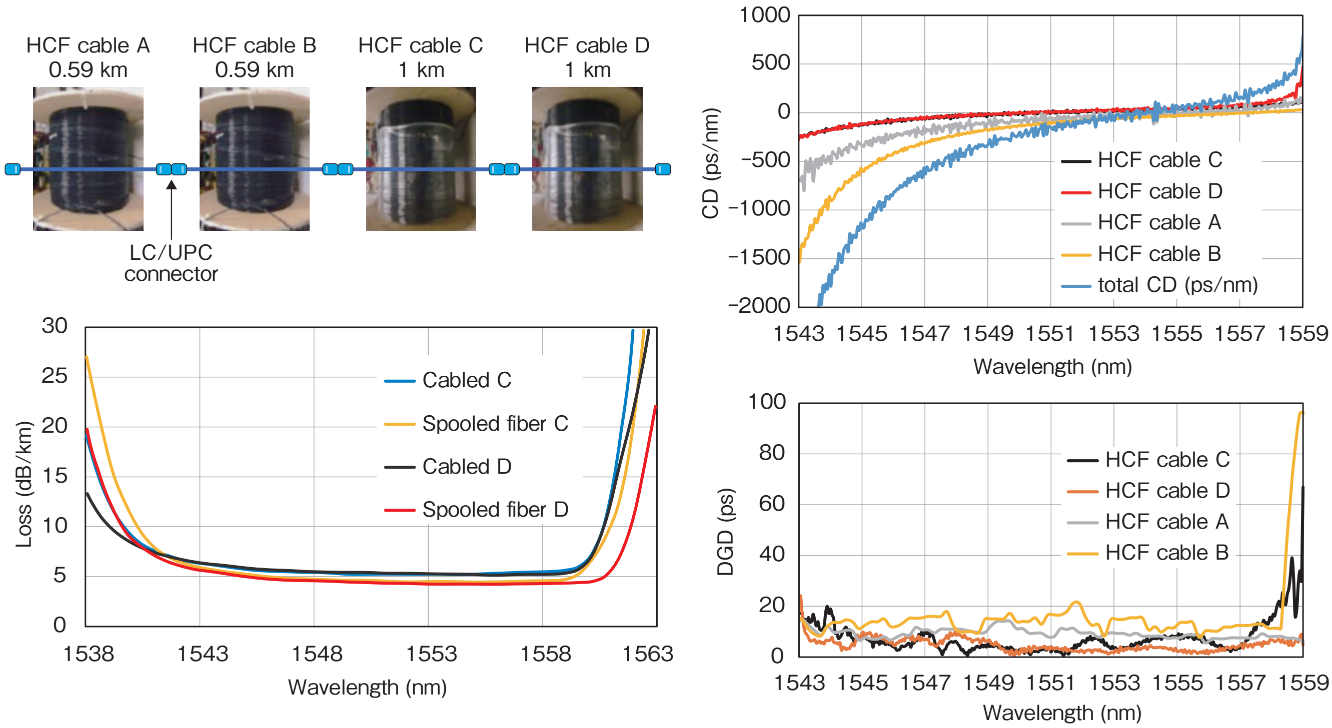

Figure 5 **Examples of structure of 6 shunt core PBGF cable, loss, wavelength dispersion and PMD characteristics.**

loss at 1571 nm was –31.3 dB, which were good results.

In addition, we also fabricated the HCF cable with Ultra Physical Contact (UPC) LC connectors fusion-spliced to the Single Mode Fiber (SMF) at both ends. The cable structure and characteristics are shown in Figure 5. Even after cabling, we confirmed that any of loss, dispersion, and Polarization Mode Dispersion (PMD) had good characteristics. Furthermore, we evaluated transmission characteristics of this HCF cable and confirmed that it also had good characteristics.

3. STUDIES TOWARD PRACTICAL APPLICATIONS OF THE HCF

Although these research results have made great progress toward practical applications of the HCF, there are still some issues to be solved before the fiber can be used in actual applications. We have further investigated these issues and will report results of our investigations.

3.1 Reliability Tests of the HCF

Although the realization of making it SM as described above has greatly accelerated their practical applications, attention tends to focus on optical characteristics such as transmission loss, dispersion, and PMD because the HCF is still a new fiber. However, for actual implementation in society, reliability test characteristics such as macro/micro bending loss, mechanical strength characteristics, etc. are important in addition to these optical characteristics. Therefore, these reliability tests were conducted on an optimized Photonic Band Gap type hollow core Fiber (PBGF) and an Anti-Resonant hollow core Fiber (ARF) having almost the same fiber diameter/coating diameter[10].

First, results of the macro/micro-bending loss measurements are shown in Figure 6. The micro-bending loss was measured using the fixed drum method (specified in JIS C6823), which is widely used for conventional fibers. Regarding the PBGF, the macro-bending loss is quite close to the ITU-T G.657A2 standard, which is a strict bending loss standard, and the micro-bending loss is also suppressed to a level similar to that of submarine Aeff-expanded fibers, but it was confirmed that the ARF has relatively large macro/micro-bending losses. The micro-bending loss was suppressed to the same level as that of Aeff expanded fiber for submarine applications, but the ARF showed relatively large macro/micro-bending loss. Therefore, while there is a possibility that the current

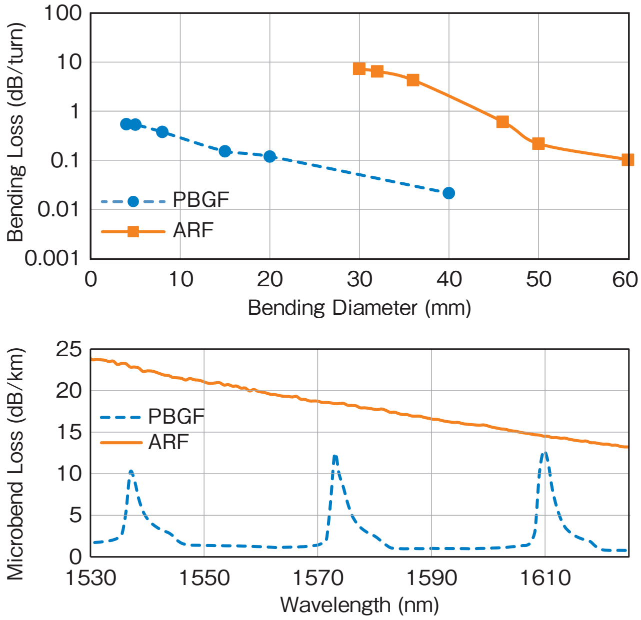

Figure 6 **Macro-bending loss (upper)/Micro-bending loss (lower) characteristics of 2 types of HCFs.**

structure of PBGF can be used in a form like the current usage, it may become necessary for the ARF to consider a new usage form. Of course, the current PBGF and ARF structures are not necessarily optimized from the viewpoint of macro/micro-bending loss, so no conclusion can be drawn from these results alone, but these characteristics must be fully taken into consideration when putting them into practical application. We plan to continue to study optimization taking these points into account.

In addition, the strength of the optical fiber is also a very important factor when considering practical applications. Therefore, we performed an evaluation of the dynamic fatigue coefficient by the tensile strength measurement (IEC60793-1-B7A standard), which is widely used as a method for evaluating the strength of optical fiber. Using two types of HCFs (ARF and PBGF) with an almost same outer diameter, we performed dynamic fatigue coefficient measurements before and after a moist heat test (85°C 85%Rh 720 h) at tensile strengths of 0.025%/min, 0.25%/min, 2.5%/min, and 25%/min. Taking into account the cross-sectional area of the glass, the fatigue coefficients (n value) before the moist heat test were 29.2 (PBGF) and 26.1 (ARF), respectively and after the moist heat test, they were 22.7 (PBGF) and 23.6 (AFR), respectively, which are comparable to the results of a standard glass core fiber. Further, additional tests and systematic studies when the structure is changed will be necessary, but this is a very important result when considering practical applications.

3.2 Fusion Splicing Characteristics of the HCF

For practical applications of HCF, the fusion splicing technology will be important in addition to the mechanical connector connection technology reported in Furukawa Electric Review No. 52. Furthermore, about the fusion splicing technology, in addition to the splicing between HCFs, the development of fusion splicing technology between the HCF and glass core fiber is required. One example of splicing same type HCFs is reported by T. Kremp et al.[11]. In this study, it was reported that a median splice loss of 0.13 dB between same type ARFs was achieved by not only optimizing the fusion splicing conditions such as a side-view rotation alignment, etc. but also using an appropriate fusion splice equipment itself such as the Fitel S185PMROF fusion splicing equipment, which provide uniform heat distribution. We are continuing to conduct research and development on the fusion splicing with an emphasis on the use of appropriate fusion splicer types.

We are also investigating the fusion splicing between HCF and solid fiber. When the fusion splicing between the HCF and the solid fiber is performed, it is difficult to achieve proper splicing because the fusion process of the HCF differs from that of the solid fiber. In addition, the same is true for the fusion splicing of HCF and HCF, but the fusion splicing which includes HCF has the problem that the structure of the HCF is disrupted during the discharge of fusion splicing, resulting in a very large loss. Figure 7 shows examples of the side and cross-sectional structures when the fusion splicing is performed without optimizing the fusion splicer or conditions. As shown below, when a fusion discharge is performed without optimization, the structure is deformed or the internal structure is partially or completely lost, resulting in very large fusion losses of, for example, 5 dB or more.

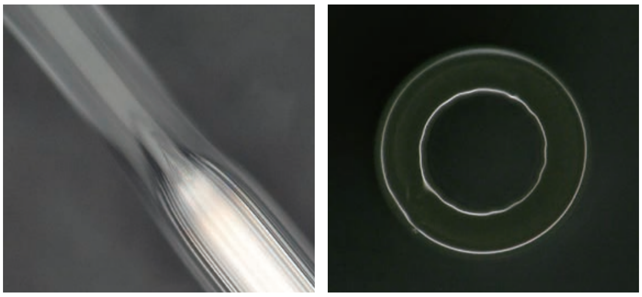

Figure 7 Side picture (left) and cross-sectional picture (right) of the HCF after the fusion splicing without optimizing conditions.

Therefore, we optimized the glass fiber to be connected, the fusion splicer, and the fusion splicing conditions, and investigated ways to reduce the fusion splicing loss. As far as the glass fiber to be connected, the Mode Field Diameter (MFD) was optimized in the same way as the connectorization study and the fusion splicing conditions were optimized to obtain low fusion splicing loss while maintaining sufficient strength. As a result, we achieved a low loss fusion splicing of 0.45 dB between the PBGF and the glass fiber. Furthermore, we achieved a low loss fusion splicing loss of 0.54 dB between the ARF and glass fiber through similar optimization. These results are also very important achievements in terms of practical applications.

3.3 HCF Cable Installation Test

As mentioned above, the research and development of peripheral technologies such as cables and connections are progressing, but for practical applications, not only the investigation of cabling, but also the actual cable installation tests in the field are necessary. Our HCF cable was installed, as shown in Figure 8, at the “Keio University Future Optical Network Open Research Center” inside the Shinkawasaki Town Campus of Keio University, and started experiments on an ultra-low latency network campus connecting multiple buildings.

The world’s first facility where engineers from all over the world can conduct experiments on the HCF in a practical environment has been completed. The cable is even installed inside manholes, recreating an actual field environment. Press releases were issued by Furukawa Electric and Keio University[12], and the details are also available on the YouTube channel below.

Interview with a related party:
“World’s First! Future Optical Network Open Research Center Connected with the HCF”
Japanese version: https://youtu.be/RObYJCngxCs
English version: https://youtu.be/8jZIj6XBzTM

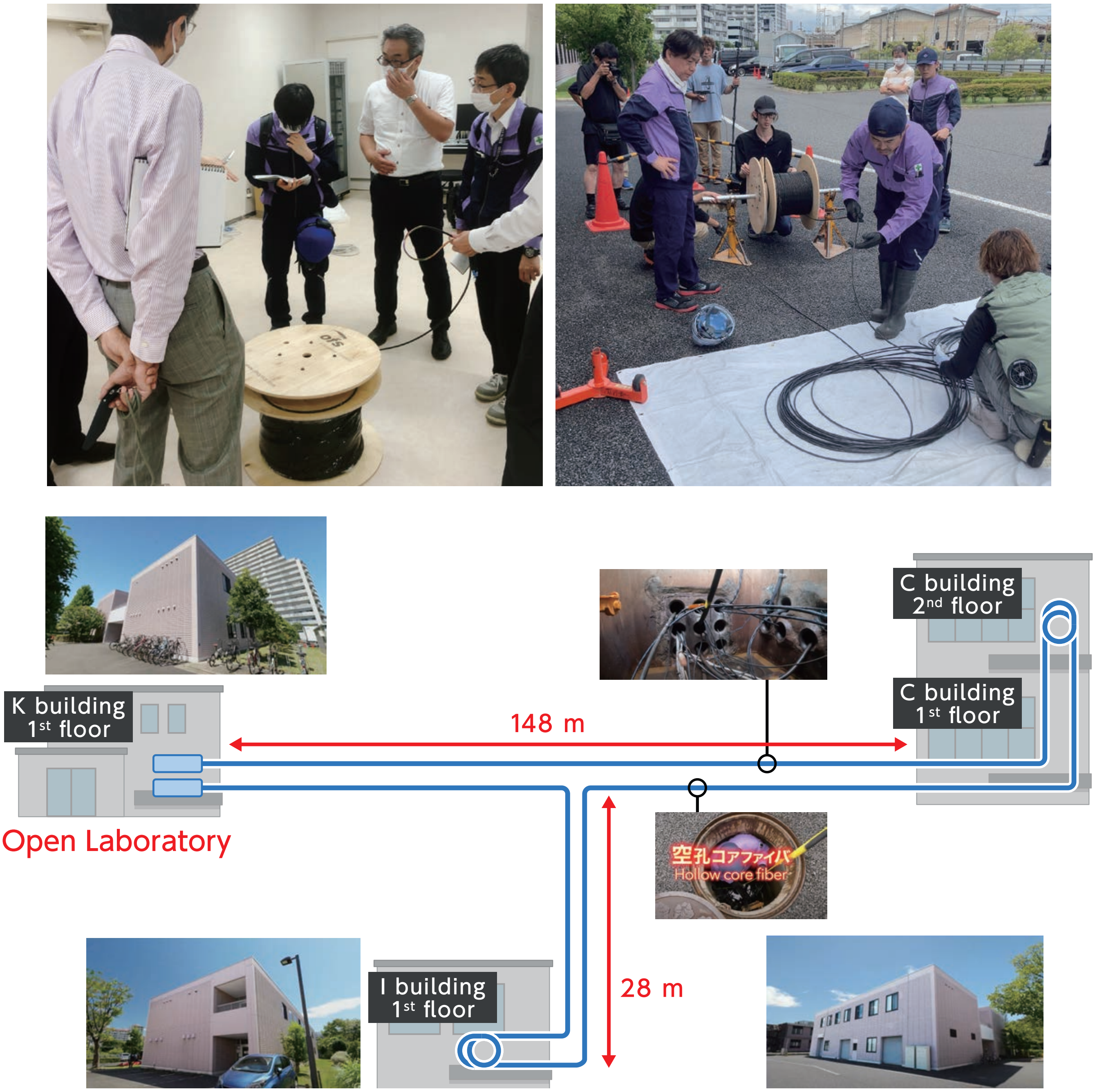

Figure 8 **Pictures and installation routes of the HCF cables installed in Keio University campus.**

It is expected that further tests will be conducted in a practical environment using this facility in the future, and that this will lead to further progress in practical applications.

One of the most important characteristics after the cable installation is the confirmation of its aging loss characteristics. We have been checking the aging loss characteristics of the HCF after the cable installation. Results are shown in Figure 9, and stable loss characteristics have been obtained over time, confirming stable characteristics that are suitable for practical applications.

3.4 Application Experiments of the HCF

To put the HCF into practical applications, in addition to the previously mentioned research and development, it is extremely important to confirm the fiber's characteristics through application experiments that simulate real world systems. Therefore, in collaboration with Keio University and the University of Electro-Communications, we are conducting several application experiments. Examples of the results are shown in Table 1. Various application experiments that take advantage of the characteristics of the HCF have been conducted, and very good performances have been demonstrated. Therefore, it has been confirmed that HCF has great potential of deployment in practical applications as well.

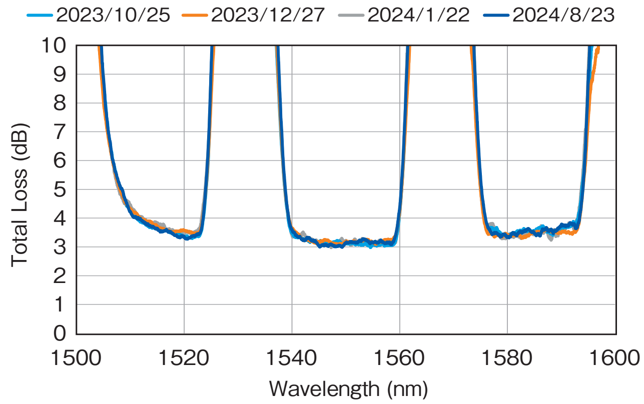

Figure 9 Aging loss characteristic over time of the HCF cable installed in Keio University campus.

Table 1 Summery of application experiments using the HCF.

No.	Items	Details
1	Reporting conference	2023 Photonics in Switching and Computing
	First author	Shunpei Kimura (Keio University)
	Title	+30.8 dBm, IM-DD, 32 Gbit/s high power optical transmission with 4-km photonic bandgap fiber
	Abstract	>+30 dBm input 32 Gb/s transmission over 4 km PBGF
2	Reporting conference	Institute of Electronics, Information and Communication Engineers PN Laboratory August 2023 Study Group
	First author	Natsuo Murakami (University of Electro-Communications)
	Title	Evaluation of transmission characteristics of fiber optic radio using hollow core fiber
	Abstract	Comparison between SMF and PBG on 1 km high power RoF transmission characteristics
3	Reporting conference	OFC 2024
	First author	Kai Murakami (The University of Electro-Communications)
	Title	Over 1-Watt Analog RoF Signal Transmission Using a 1-km Hollow-Core Photonic Bandgap Fiber
	Abstract	Analog RoF Transmission Characteristics of >1 W over 1 km PBGF
4	Reporting conference	The 6th Optical Wireless and Fiber Transmission Conference 2024
	First author	Hironori Yamaji (The University of Electro-Communications)
	Title	Simultaneous Data and Power Transmission Using a Hollow-Core Fiber for Passive Optical Network
	Abstract	Confirmation of >5 W RoF signal transmission and 14.4% power transmission efficiency using 1 km PBGF and 8-branch PON
5	Reporting conference	Yeah, now the sound is there, the reality of the world, things 2024
	First author	Naoaki Yamanaka (Keio University)
	Title	Disaggregated Computing Access Network using Newly Structured Hollow-Core fiber for AIoT Platform
	Abstract	Proposal of Space time Synchronous Digital Twin for AIoT Platforms Using Open Lab Hollow Core Fiber Low Latency Networks
6	Reporting conference	Institute of Electronics, Information and Communication Engineers, PN Research Institute, August 2024
	First author	Satoshi Okamoto (Keio University)
	Title	Local 5G over PON construction experiment using campus installed hollow core fiber
	Abstract	Construction of a Local 5G over 10G-EPON system using the installed hollow core fiber cable
7	Reporting conference	ECOC2024
	First author	Ryuta Murakami (Keio University)
	Title	First Demonstration of Switched RoF Concept Using MEMS Optical Switch and High-linearity Installed Hollow Core Fiber Cable
	Abstract	Installation experiment of optical switch to Analogue RoF system using the installed hollow core fiber cable
8	Reporting conference	ECOC 2024
	First author	Souya Sugiura (The University of Electro-Communications)
	Title	Demonstration of power-over-hollow-core-fiber with 5G NR signals for optically powered remote antenna units
	Abstract	Simultaneous transmission of 5G NR signals and optical power supply using a hollow core fiber

4. CONCLUSION

The research and development of the HCF has made significant progress. Following the successful development of making HCF SM, realizing the HCF connector, and successful cabling of the HCF reported in Furukawa Electric Review No. 52, we have achieved confirmation of good reliability characteristics, advanced HCF fusion splicing technology, successful HCF cable installation experiments, and numerous successful application experiments, making further progress toward practical applications of the HCF. With such comprehensive research results toward practical applications, the rapid expansion of practical applications of the HCF is just around the corner.

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