Very-low-delay massive wavelength division multiplexed optical network using Newly structured hollow-core fiber and its application (Invited talk)

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***Abstract*— Newly structured fiber called Hollow-Core Fiber (HCF) had been equipped into the campus for ultra-low latency network. In Keio university's open lab, we constructed HCF network among four building. HCF transfers the optical signal through the air core not glass core materials. Therefore, three main futures are achieved as follows: 1st is Ultra high-power transmission having 1,000 times larger which can apply to energy transmission like power over fiver (PWoF). 2nd is very-low delay because of small refractive index of about 1. 3rd is optical transmission without degradation due to optical non-linearity which can apply to analog signal transmission for example radio over fiber (RoF). So that we propose massively-wavelength parallel optical paths with HCF to realize the ultra-low latency path. We will use multi-band including S, C, L-Band etc. And using less-nonlinearity, denser wavelength can be transmitted. Because we can use huge number of wavelengths, so one user uses one wavelength without packet or flame multiplexing. So multiplexed delay can me neglected. This paper also describes other new futures such as analogue radio over fiber (ARoF) for 5G signal extension tested in the Keio university future optical network open research center. These technologies will be key to a reliable and smart Beyond 5G society.**

Keywords*— Beyond 5G, Low latency, Hollow-core fiber, Optical Network, IOWN, Digital Twin

I. Introduction

In the 21st century, optical networks have made great progress as high-speed, wide-band link technologies, and computer science services such as cloud services have been enriched. In the next generation Beyond 5G, further development is being encouraged in seven areas in particular [1, 2], among which ultra-low latency and energy saving are given high priority as shown in Fig.1. Ultra-low latency services are in high demand for new smart social services such as robot control and autonomous driving. To achieve very-low latency, not only network architecture, but also both system and device improvement are needed [3]. On the other hand, low power consumption is also a goal of the sustainable development goals (SDGs), and there are high expectations for optical technology, which can achieve power savings of 1/500 to 1/1,000 compared to electricity. This article describes in detail the status and goals of the research conducted by Keio University's "Keio Future Optical Network Open Research Center"' which has been underway since 2023.

II. Keio Future Optical Network Open Research Center

Once again, we set out to achieve a major breakthrough in low power and ultra-low latency using optical networks. In order to achieve ultra-low latency, a breakthrough from not only protocol level but also the device level is essential, and at the same time, we would like to aim for a paradigm shift that vertically integrates networks, systems, and even their applications. In that case, a system that collaborates with researchers and engineers, including many application researchers, is essential. Fig. 2 shows the Keio Future Optical Network Open Research Center [4, 5], which was created in April 2023 with support from the Ministry of Internal Affairs and Communications (MIC) of Japan. This is a research center that has installed the world's only Hollow-Core Fiber (HCF) cables on its campus [4], which will be described in the next chapter, to achieve ultra-low latency not only on the rack or in the floor but also on the multi-building campus. This center is an open laboratory that can be used by researchers from domestic and international companies and universities by sharing their research objectives. We are also aiming to collaborate with open labs in the United States, and we are working to create a global consortium [5].

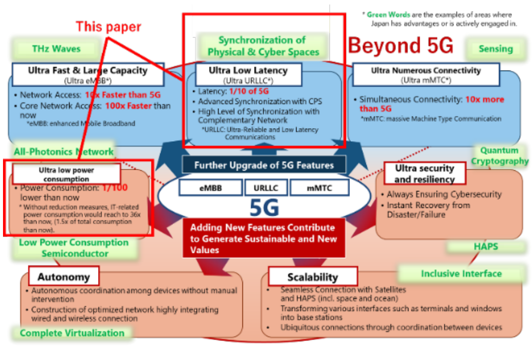

Fig. 1. Target for beyond 5G [1].

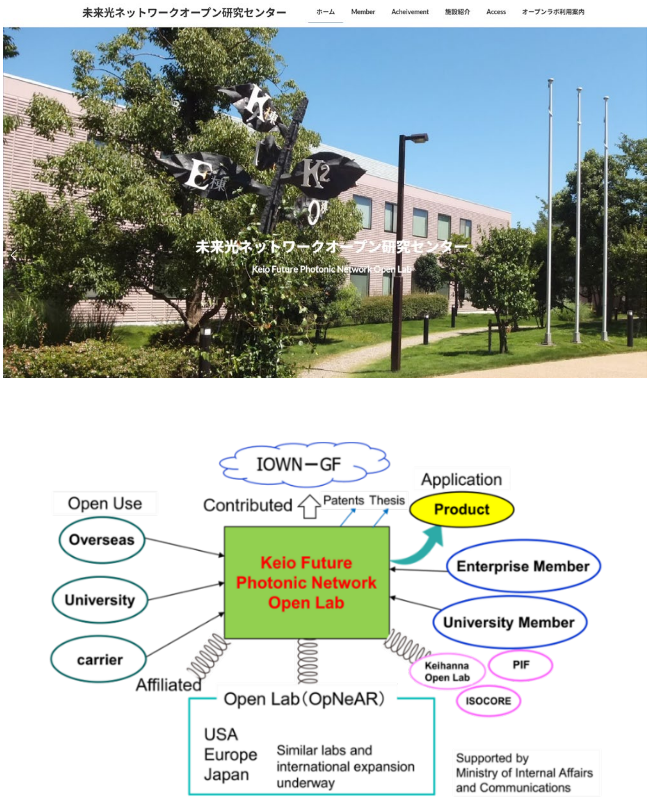

Fig. 2. Photo and structure for Keio Future optical network open research center.

III. FUTURE METRO / ACCESS NETWORK ARCHITECTURE FOR MASSIVE-IOT USER

A. Next generation extremely multiple access network

The MIC's Research and Development of Advanced Optical Transmission Technology Contributing to a Green Society (JPMI00316) (research representative: Oki Electric Industry) [6] is proceeding with research and development using the network architecture shown in Fig. 3. This is an economical ultra-high-speed passive optical network (PON) technology in the 400 Gbps class for distributed cloud access and a super multi-branch PON technology that covers IoT and sensors. Current PON mainly covers residential use, and it is said that reliability and bandwidth are still insufficient for mobile backhaul, cloud red and edge computing. On the other hand, devices such as IoT and sensors that use almost no bandwidth, and devices such as sensor cameras that are only used when someone is present and are turned off the rest, have also entered subscriber networks. Taking these into account, Beyond 5G is also considering super multi-branch access for economical solution.

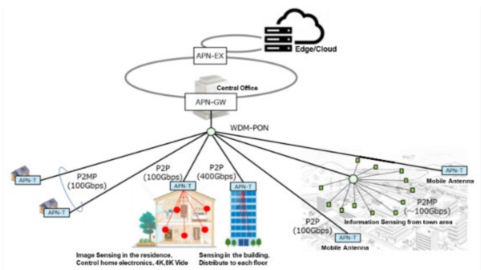

Fig. 3. Next generation access network architecture by JPMI00316 project.

B. Hollow-Core Fiber (HCF) [7]

Fig. 4 shows the structures of an ordinary single-mode fiber (SMF) and an HCF with a cross-sectional photograph [7]. This HCF is categorized in the photonic bandgap (PBGF) type HCF. There is another structure called anti-resonant type hollow core fiber [8, 9] but because of better performance for real use, we use the PBGF-type HCF. PBGF-HCFs have a crystal structure in their cladding, and the diameter of the core portion, where light is successfully confined in the air portion of the core through Bragg reflection, is larger than that of ordinary single-mode fibers. Since the core is air and refractive index of air is very small (n = 1.0003), the following three major characteristics are expected. do not differentiate among departments of the same organization).

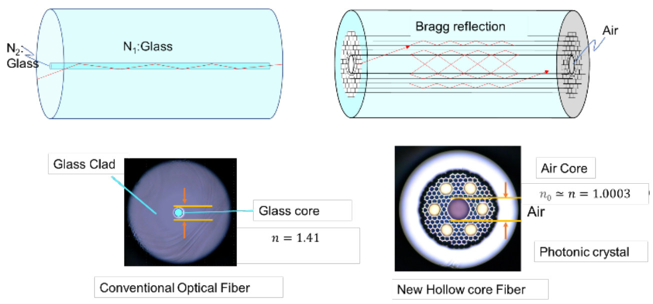

Fig. 4. Image of optical transmission using hollow core fiber and its cross-sectional view (large size adjusted).

#1. High energy transmission is possible...approximately 1,000 times that of normal optical fiber (e.g. SMF).

#2. Low delay...$v = C/n$ and $n = 1.0003$ (C is the speed of light: 3×10^8 m/s), normal optical fiber is $n = 1.47$. There are some demonstrations related to low delay [10,11,12,13]. This is one of the very important characteristics for Beyond 5G.

#3. Expected high linearity…no nonlinearity depending on the core material. This characteristic is a new future for optical transmission [14].

From #1, there is a possibility of realizing power over fiber (PWoF)[15] and ultra-multi-wavelength transmission [16] because there is a low limit on energy density increasing in proportion to the number of wavelengths. In #2, there is a possibility of a low-latency network. Regarding #3, there is a possibility of analog radio over fiver (ARoF) [17, 18]. Below, we will discuss the research status of the latest technology.

IV. ULTRA-LOW DELAY, MASSIVELY PARALLEL OPTICAL NETWORK RESEARCH

A. Multi-band and fine pitch interconnection [19]

Fig. 5 shows the delay time when multiplexing into a high-speed optical link by packet multiplexing. When packet multiplexing is performed on a single wavelength in a high-speed optical link (e.g., 100 Gbps or 400 Gbps), a queuing delay occurs. On the other hand, when time division multiplexing or packet multiplexing is not required for a single wavelength per user at low speed of 10 Gbps, this massive wavelength multiplexing does not cause delay. In addition, forward error correction (FEC) is required for links for from 100 to 400 Gbps. On the other hand, 10 Gbps links do not require FEC, which is advantageous in terms of latency and power consumption. In addition, if Intensity Modulation-Direct Detection (IMDD) communication can be used instead of digital coherent technology [20], which has been the mainstream in recent years, power consumption, which has been caused by digital signal processor (DSP), can be eliminated. Therefore, significant reduction in transmission power consumption can be achieved. Fig. 6 illustrates the current explanation.do not differentiate among departments of the same organization).

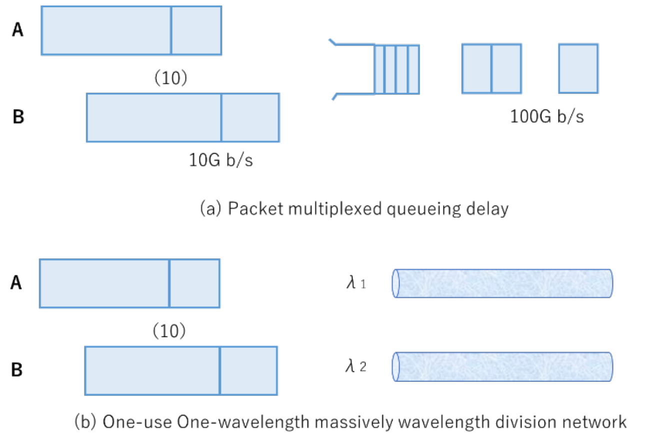

Fig. 5. Delay caused by multiplex.

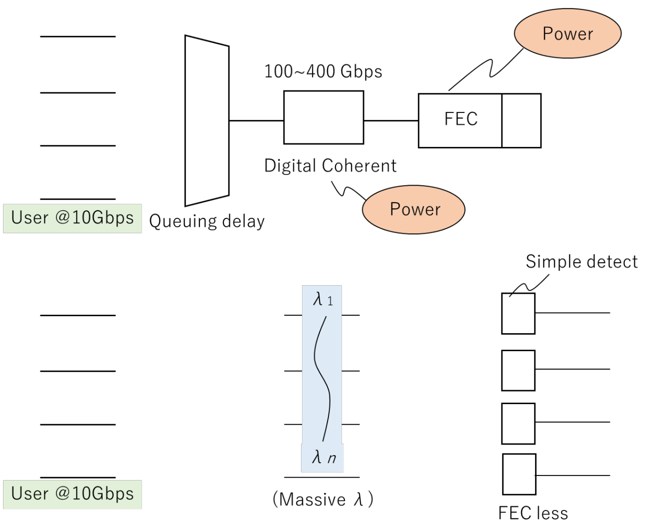

Fig. 6. Lower power and shorter delay inter connection.

To achieve this, it is necessary to realize communications with 100 to 1,000 times the number of wavelengths as described before. Optical fiber has T, O, E, S, C, L, and U bands as communication bands. Currently, C-band optical fiber communication is the most commonly used band, taking advantage of the low loss of optical fiber, and S- and C-bands are used at most. As shown in Fig. 7, multiband and low-loss characteristics are expected compared to conventional glass single-mode fibers [21]. Dotted line is theoretical ideal loss for HCF. However, to use multiband, other technological elements, such as light sources and amplifiers, must also be developed.

On the other hand, to use many wavelengths in one band, it is necessary to narrow the pitch between channels of wavelength of fine-pitch wavelength division multiplexing (WDM) technology as shown in Fig. 8. When the pitch is made fine and signals are sent at high power using the characteristics of the HCF, a nonlinear reduction called four-wave mixing (FWM) occurs in the conventional SMF.

Fig. 9 shows the experimental results of FWM between a conventional SMF and a PBGF-type HCF [26]. As can be seen, nonlinear effects are hardly observed in the HCF.

To realize massively parallel wavelength multiplexed network, as shown in Fig. 10, the fine pitch wavelength selective switch (WSS), which is one of the most important wavelength devices in this project. Details will be reported by another conference.

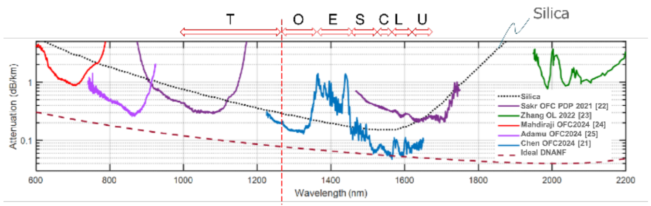

Fig. 7. *Multi-band transmission loss for SMF and Hollow-core fiber based on [21].*

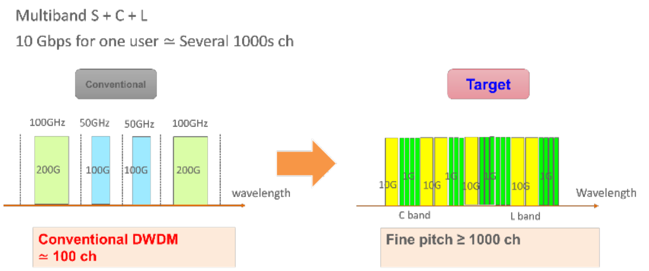

Fig. 8. *Fine pitch WDM for one lambda for one user.*

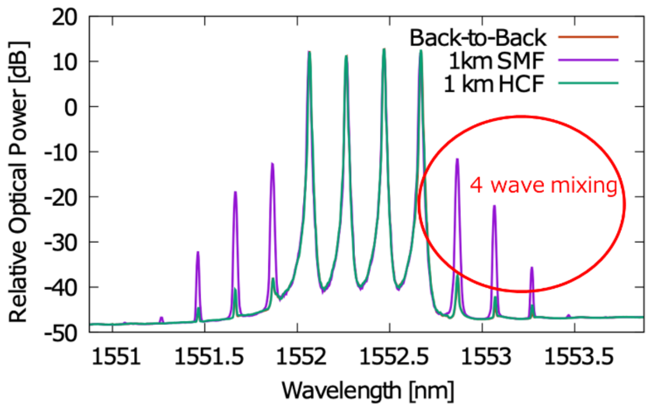

Fig. 9. Four wave mixing effect for conventional SMF and Hollow-core fiber

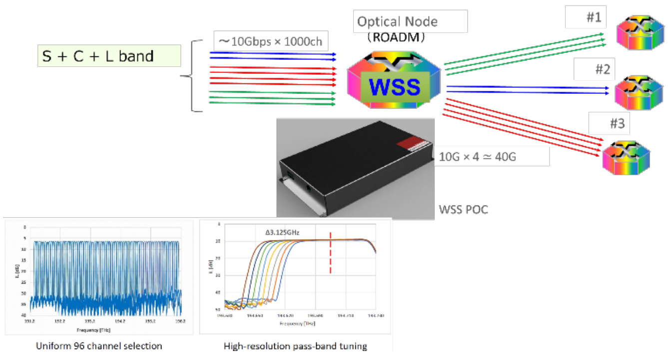

Fig. 10. Fine pitch WSS overview and characteristics.

B. Analog Radio over fiber (ARoF) [27]

We have started experimenting with ARoF using PBGF-type HCF [28]. Currently, 5G uses radio in the sub 6 GHz (sub-6) band. Furthermore, in the pursuit of broadband communications, it is important to utilize millimeter wave bands exceeding 20 GHz and THz. On the other hand, since these high-frequency bands have excellent straight-line propagation, they are greatly affected by buildings and obstacles. ARoF allows antennas to be installed behind these obstacles using optical fiber and can also complement wireless technology. We also succeeded in transmitting WiFi using ARoF [29, 30]. A photo of the module is shown in Fig. 11. The Keio Future Optical Network Open Research Center is equipped with sub-6 private 5G (called "Local 5G" in Japan) equipment. We have started experimenting with RoF using this system (Fig. 12) and HCF. We have also started experimenting with Switched-RoF/MultiSpot-RoF [18, 31], which uses optical switches (or splitters) to selectively output wireless signals to multiple ARoF antennas.

Fig. 11. ARoF module.

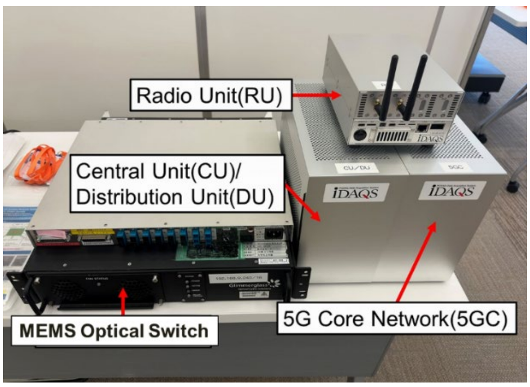

Fig. 12. Local 5G system and micromachine electro mechanical system (MEMS) optical switch.

C. Ultra-low latency network test bed

Fig. 13 shows the world's first HCF campus installation diagram. A newly developed cable was installed inside the manhole, making it possible to conduct research at a level close to practical use [32].

Fig. 13. Example of a figure caption. (*figure caption*)

V. CONCLUSIONS

We have built a campus network using PBGF-type HCF, aiming for a breakthrough from devices that will meet the ultra-low delay requirements of Beyond 5G. HCFs have an air hole in the core and have succeeded in trapping light in the core. Using the characteristics of this fiber, we first reported on the current experimental results regarding the possibilities of multi-branch access, ultra-multi-wavelength networks, and analog radio over fiber with some experimental results. We also opened the Keio Future Optical Network Open Research Center to make these available for open use. HCF has other capabilities like multi-band transmission and massively huge number of wavelength transmission with more sophisticated transmission technologies [33, 34]. We will be expanding our research on this area.

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In addition, experiments and research were conducted at the Keio University Future Optical Network Open Research Center. This new functional fiber was developed mainly by Furukawa Electric and OFS.

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