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C O N T E N T S

About ITU-AJ

The ITU Association of Japan (ITU-AJ) was founded on September 1, 1971, to coordinate Japanese activities in the telecommunication and broadcasting sectors with international activities. Today, the principle activities of the ITU-AJ are to cooperate in various activities of international organizations such as the ITU and to disseminate information about them. The Association also aims to help developing countries by supporting technical assistance, as well as by taking part in general international cooperation, mainly through the Asia-Pacific Telecommunity (APT), so as to contribute to the advance of the telecommunications and broadcasting throughout the world.

EXAT Study Group: 15 Years of Progress

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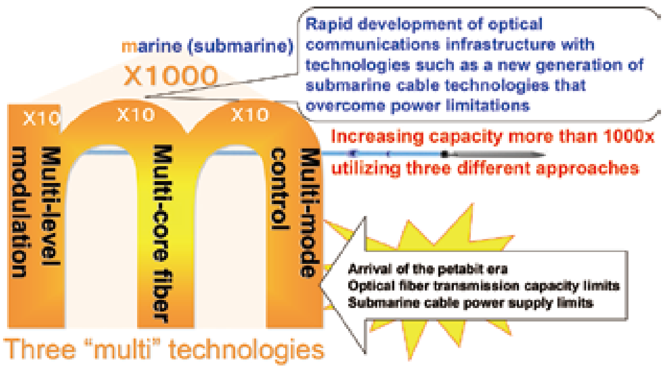
1. Introduction

This special feature gives a summary of the presentations given at the "Symposium on Extremely Advanced Optical Transmission Technologies—EXAT (3M): celebrating 15 years of research activities" organized by the Institute of Electronics, Information and Communication Engineers (IEICE) Communications Society, EXAT Study Group[1] on December 11, 2023 in Tokyo. The EXAT Study Group[2], initiated under the leadership of the National Institute of Information and Communications Technology (NICT) in January 2008, moved its activities to the IEICE Communications Society as a technical committee in April, 2010, and is currently leading the world in the latest optical fiber communications technologies. Since then, the transmission capacity of a single optical fiber has increased by approximately three orders of magnitude, from approximately 32 terabit/s to 23 petabit/s, using its proposed "3M Space-division multiplexing optical transmission technology" (multi-core fiber, multi-mode control, multi-level modulation) (Figure 1). This article gives an overview the 15-year history of the group's activities, including the early days from 2008 to 2009, active international collaboration activities as the IEICE EXAT technical committee starting from 2010, EXAT-related national projects funded by NICT and the Ministry of Internal Affairs and Communications (MIC), and its efforts towards commercialization.

Figure 1: 3M technologies enabling 1,000 times transmission capacity



2. Birth of the NICT EXAT Study Group (2008-2009)

Considering that communications traffic was increasing rapidly, at roughly 40% per year (three orders of magnitude increase in 20 years), the "EXtremely Advanced optical transmission Technologies study group" (EXAT Study Group) was formed in January 2008, under the leadership of NICT, to lead the world in creating new optical transmission line and optical transmission technologies and increase transmission capacity by more than three orders of magnitude. During the initial period (2008), roughly 25 members from industry, academia and national institutes discussed the limits of current technologies, new optical fibers able to transmit well over petabit/s, and new transmission technologies such as space-division multiplexing (SDM), which could surpass time-division multiplexing (TDM) and wavelength-division multiplexing (WDM). To ensure practical implementation in the future, the study group consisted of leading young researchers in optical communications, those with experience in commercializing optical communications systems, and those who were actively involved in international standardization at ITU, IEC, etc. The second period (2009), included discussion of technical topics toward creation of new national projects related to the technologies studied in the initial period, with collaboration among industry, academia and government. The name of the study group, EXAT, is an abbreviation of "EXtremely Advanced Transmission," but it also implies "Exabit/s transmission technology" (EXA=10^{18}). In November 2008, the EXAT2008 International Symposium was held in Tokyo, together with debriefings of the first-term activities. It attracted approximately 200 participants and included discussion of R&D directions for world-leading new optical fiber and SDM transmission technologies.

3. International activities of the IEICE EXAT Study Group (from 2010)

Following the activities of the NICT EXAT Study Group, in April 2010, the IEICE Communications Society initiated the "Time-limited Technical Committee on Extremely Advanced Optical transmission infrastructure (currently the Ad-Hoc Technical Committee)"[1] to promote and encourage this technical field around the world and promote even wider discussion on technology research strategies toward next-generation optical communications infrastructure. To date, it has sponsored seven international symposia, including EXAT2008, technically co-sponsored workshops and symposia at 23 international conferences, and actively promoted international collaboration activities. Also, as part of our efforts to refine the technology roadmap for this field and contribute to its implementation in the society, we have completed Version 2[3] of the roadmap for standard cladding diameter multi-core fibers.

Recently, standard cladding diameter multi-core fiber technology has attracted international attention as the first milestone toward practical deployment of space-division multiplexing transmission, and this technology was positioned as one of the candidates for deploying space-division multiplexing optical fiber in a technical report on space-division multiplexing optical fiber cable issued by ITU-T SG15 in 2022[4]. The studies and proposals in this technical report were based on contributions from Japan, including from members of the EXAT Study group. Regarding the roadmap and international standardization trends, see "Activities concerning the EXAT Roadmap and Trends in Standardization of SDM Optical Fiber" in this special feature. Progress in technologies studied by the EXAT Study Group is described in detail in both Japanese[5] and English[6] publications.

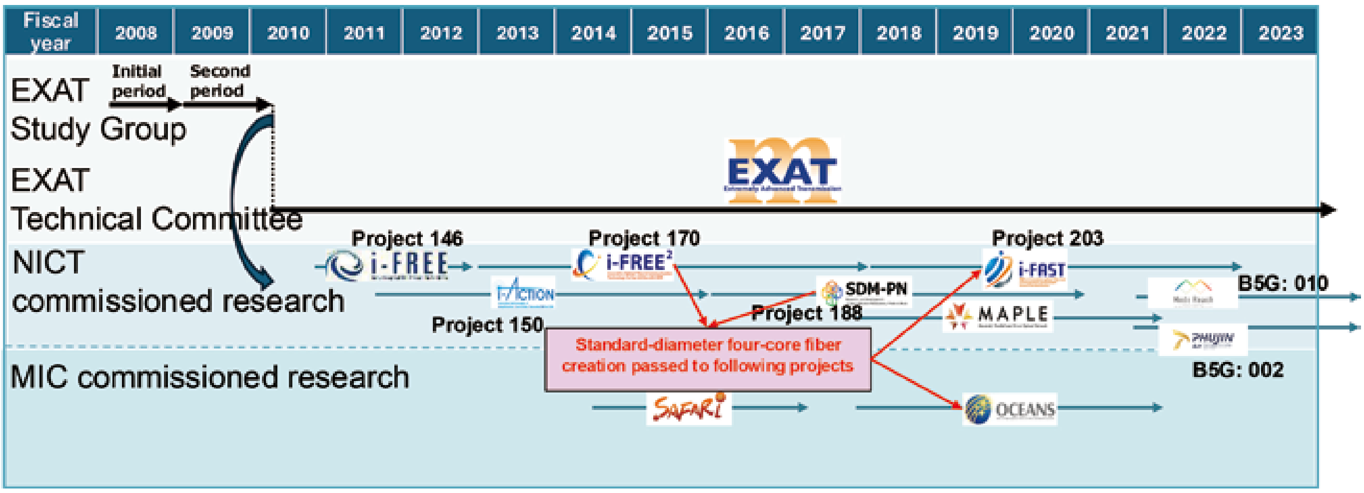
4. NICT/MIC EXAT-related national projects

Figure 2 shows the progress of the EXAT Study Group from its initiation to the present, including industry-academia-government collaboration projects.

Regarding research collaboration in Japan, NICT prepared an All-Japan R&D program, mediating and coordinating a framework among several communications carriers striking a balance among industry, academia and government by helping with planning for elemental technologies, according to business conditions for the major fiber manufacturers and vendors, with universities committing to fiber design and theoretical study from 2009 to 2010. As of 2010, SDM technology was a fledgling technology, so as a first step, public funds were invested to accelerate high-risk R&D and obtain certain results. This increased opportunity to form an international consensus on the technology and initiate projects, gradually expanding investment from private enterprise and transitioning smoothly to enterprises and commercialization.

More specifically, the NICT Advanced Communications and Broadcasting R&D Commissioned Research Program was used to carry out steps of an ongoing R&D program with participation from multiple enterprises and universities. The first project was Project 146 "Innovative Optical Fiber Technologies" (i-FREE), conducted for three years starting in 2010, which was the first project in history on the design, fabrication and performance evaluation of multi-core fiber for communications. As background, the project initially aimed to "realize petabit/

Figure 2: EXAT Study Group from its initiation to the present



s-class optical communications within five to ten years," but somehow it managed to achieve one petabit/s transmission within two years (see below). Then, Project 150 "Innovative Optical Communication Infrastructure" (i-ACTION) was conducted from 2011 to 2015, establishing three main components of a multi-core fiber optical transmission system: multi-core optical amplifier technology, multi-core fiber connection technology, and a multi-core/multi-mode transmission technology. This last item incorporated multi-mode transmission, which had become established in Europe and the USA as a competing technology for multi-core fiber. With the completion of this and Project 146, the prospects for a first-stage multi-core fiber optical transmission system came into view. Note also that in 2012, while Project 150 was in progress, petabit/s transmission using 12-core fiber was achieved [7].

Later, the successor to Project 146, Project 170 "Innovative Optical Fiber and Communication Technology for Exabit Era with SDM" (i-FREE[2]) (2013 to 2017), involved more-focused research on multi-core fiber, including multi-core fiber design principles, establishing fabrication methods, evaluation indices to reduce losses and interference between cores, strengthening analytical and numerical theory, study of few- and multi-modes, achieving both performance and manufacturability, technical development such as Fan-In/Fan-Out devices, and drafting the first action plan toward standardization. Then in the following Project 203 "R&D on Innovative Optical Fiber and Communication Technologies Toward Standardization" (i-FAST) (2018 to 2022), standard cladding diameter multi-core fiber, which was invented during running of Project 170 and Project 188 (described below), was prioritized to implement quickly. R&D focused on fabrication technologies for standard cladding diameter multi-core fiber to improve mass-production, related technologies such as cabling, and evaluation technologies.

The successor to Project 150 was Project 188 "R&D of Space-Division Multiplexing Photonic Node" (SDM-PN) (2016 to 2020), focusing on a high-capacity switching technology with 10 petabit/s-class node throughput able to accommodate the link transmission capacity increase from multi-core fiber. This involved R&D on components of the node, including evaluation methods assuming space-division-multiplexing node architecture and system control, optical amplifiers in the space-division multiplexing node, and wiring technology optimized for path-control technology and space-division multiplexing. The MIC Strategic Information and Communications R&D promotion project also had an R&D program promoting implementation in society in various ways, including "Scalable And Flexible optical Architecture for Reconfigurable Infrastructure" (SAFARI), which promoted Japan-Europe collaboration in applicable technical fields, "R&D on High Capacity Multi-core Fiber Transmission Systems" (OCEANS), which is a key ICT technology R&D project specializing in submarine cable systems, and "Ultra-high-speed and Low-power Consumption Optical Network Technologies", which includes multi-core fiber connection technology.

Projects under the NICT Innovative Information and Communications Technology (Beyond 5G (6G)) Fund Project, such as Project 002 "R&D of Space-division Multiplexed Optical Network and Node Technology" (PHUJIN) and Project 010 "R&D of Spatial-Mode Controllable Optical Transmission System" (Mode Reach), are also on-going, implementing the latest advances, but also conducting leading-edge R&D to aim for sustainable "Extremely Advanced Optical Communications Infrastructure".

5. Toward commercialization

Research on the standard-cladding-diameter multi-core fiber concept began in Project 170 and Project 188 of the research collaboration described above, with the goal of creating a practical technology quickly, was carried on mainly by their successor, Project 203, and the MIC OCEANS project. In these two projects, the technology has matured within a framework for collaboration among various companies, with the result that Japanese enterprises have continued to accumulate the technologies even after these projects ended, and in the fall of 2023, Japanese fiber manufacturers began the world's first mass production of multi-core fiber, and a US platform service provider announced plans to introduce it into their transpacific cable systems[8]. These represent the first commercialization of multi-core fiber, and the first signs that it is being industrialized and commercialized smoothly, as planned in 2010.

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Development and Future Outlook of High-capacity Optical Transmission Systems

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1. Introduction

This paper describes the development to date of high-capacity optical transmission systems that make full use of the low-loss and broad-bandwidth characteristics of optical fiber and discusses the outlook for new technologies driving a paradigm shift in the future. We take up, in particular, the terrestrial optical network and submarine cable system as typical high-capacity optical transmission systems[1], describe the historical development of each based on differences in system requirements such as installation envirnment and equipment configuration, and discuss future technical trends.

2. Progress and Future Outlook of Terrestrial Optical Transmission System

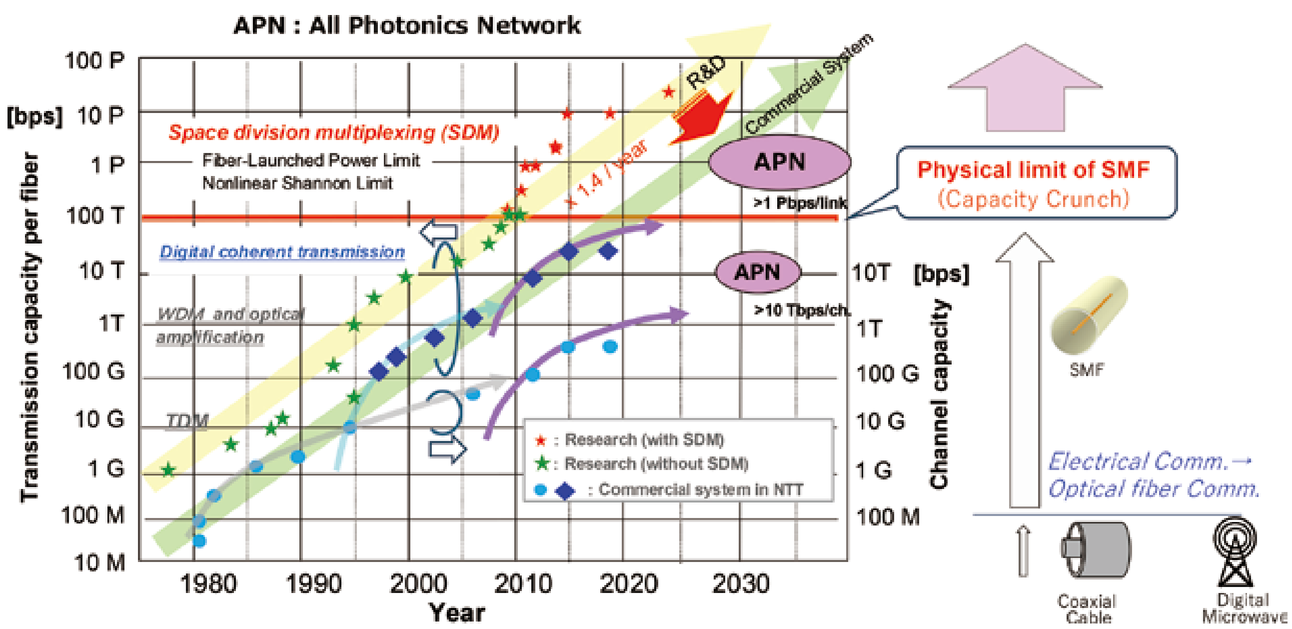
This section describes recent progress in the terrestrial optical transmission system, current technologies, and outlook for the future.

2.1 Expansion of Link Capacity in the Terrestrial Trunk Transmission System

Progress in the development of Japan's terrestrial trunk optical network are shown in Figure 1. Japan's first terrestrial trunk optical network was a 32 Mbit/s regeneration repeater system using multi-mode optical fiber (MMF) deployed for short hauls in 1981. Then, taking a global lead in the early deployment of fundamental technology using single-mode optical fiber (SMF), an optical fiber cable transmission network throughout Japan using SMF was completed in 1985 at Nippon Telegraph and Telephone Public Corporation. In the terrestrial optical network, the installation plan has been to increase capacity by using existing optical fiber cables and replacing repeater equipment while maintaining backward compatibility with repeater spacing in the existing system. Up to now, by overlaying many innovative and paradigm-shifting repeater transmission technologies, optical inline amplified transmission systems based on SMF has progressed by leaps and bounds increasing capacity by approximately six orders of magnitude over a 40-year period.

Up to the mid-90s, higher capacities were achieved by increasing the speed of a single-wavelength system through time-division multiplexing (TDM) using an intensity modulation direct detection system. In 1987, an F-1.6G system applying a 1.5-µm-band single-mode laser (single-wavelength, 1.6-Gbit/s

■ Figure 1: Change in link capacity of terrestrial optical network and paradigm-shifting elemental technologies



regenerative repeater system) was deployed, and in 1996, an FA-10G system using an erbium-doped fiber amplifier (EDFA) repeater (single-wavelength, 10-Gbit/s inline-amplified repeater system) was deployed. Then, in the 2000s, by applying wavelength-division multiplexing (WDM) and a broadband inline-amplified repeater system, even higher capacities were achieved through a 10-Gbit/s-channel-based WDM system with a 1-Tbit/s-class link capacity. In the existing terrestrial optical network, typical regenerative repeater spacing between main network nodes is 500–1,000 km with an optical inline-amplified repeater spacing of approximately 80–100 km. These optical inline-amplified repeaters amplify and transmit WDM optical signals while compensating for losses occurring within the optical fiber and optical devices. In the 2010s, advances were made in spectral efficiency and long-haul transmission in the WDM system through digital coherent technology making full use of multi-level digital modulation/demodulation signal processing technology. In 2013, a WDM optical network was deployed with a link capacity of 8 Tbit/s using 100-Gbit/s channels (polarization multiplexing, quadrature phase shift keying (QPSK) modulation), and from 2017 on, an inter-data-center network and long-haul WDM optical network were deployed with a 20-Tbit/s-class transmission capacity using 400-Gbit/s channels (multi-carrier 16 quadrature amplitude modulation (16-QAM)).

2.2 Higher Capacities through Multi-band WDM Transmission Technology

In terrestrial long-haul optical networks, the average number of fibers in one cable is several hundred, and for the time being, studies are underway to increase capacity by making effective use of existing SMF resources. Up to now, it's been mainly optical amplifier repeater systems using approximately 4.5 THz as a single EDFA optical amplifier band such as the C-band or L-band that have already been installed in commercial systems. However, given the significant advances made in spectral efficiency in recent years thanks to the practical application of digital coherent technology, it is becoming difficult to make significant improvements in spectral efficiency going forward. Furthermore, as a result of recent research and development, it has been found that there is a physical limit to SMF link capacity of around 100 Tbit/s (capacity crunch) in long-haul transmission as shown in Figure 1 due to factors such as signal distortion caused by an optical nonlinear effect and laser safety issues in terms of allowable fiber-launched power limits. Consequently, to achieve higher capacities in the 100-Tbit/s class using SMF from here on, studies are being conducted on the practical application of multi-band long-haul transmission technology using the C+L band (approximately 9 THz) and beyond to speed up WDM channel capacities and keep a certain number of wavelength channels per WDM system (about 100 ch). Two 1,000-km-class, 3-band optical amplifier repeater transmission experiments (80-km repeater span) [2, 3] have recently been reported as examples of transmission experiments with an over-100-Tbit/s-class link capacity that considers SMF allowable power limits and optical nonlinear effects such as spectral gain tilt caused by the inter-band stimulated Raman scattering effect.

2.3 Higher Capacities through Spatial Multiplexing Transmission Technology

As a technology that can fundamentally avoid the capacity crunch in long-haul high-capacity optical transmission systems, the importance of space-division multiplexing (SDM) was promoted by the Extremely Advanced Optical Transmission Technologies (EXAT) Study Group established in 2008[4]. Since then, Japan has taken the lead in this field and various types of research and development represented in this special issue have been progressing on a global basis. Of particular interest here were transmission systems using multi-core fiber (MCF), and in the 2010s, the limits of long-haul high-capacity transmission systems were vigorously pursued and studied to both increase the number of cores per a single strand of optical fiber and suppress inter-core crosstalk. In particular, weakly coupled MCF based on single-mode cores that can suppress inter-core crosstalk by controlling the refractive index profile and core arrangement has the advantage of using conventional transmission equipment using digital coherent technology for SMF. To realize 12-core weakly coupled MCF with the same refractive index core profiles (homogeneous cores) while maintaining mechanical reliability of the fiber, the cladding diameter of the developed 12-core fiber was set to 250 μm or less, which is about two times larger than that of existing SMF. Using this 12-core fiber in conjunction with multi-band WDM transmission technology using the 11-THz band comprising the C-band and extended L-band as an optical amplifier band, the first 1 Pbit/s non-repeatered transmission experiment (50 km) was reported[5]. Then, in 2017, as part of a Japan-EU coordinated funded project called Scalable And Flexible optical Architecture for Reconfigurable Infrastructure (SAFARI), the world's first 1-Pbit/s inline-amplified unidirectional transmission experiment was reported extending over 200 km using low-inter-core-crosstalk 32-core MCF with a cladding diameter less than 250 μm[6]. This was achieved by suppressing inter-core crosstalk by a 32-core heterogeneous MCF structure having two types of refractive indices. To realize a low-power and compact multi-core optical amplifier, only the C-band was used as an optical signal bandwidth. The feasibility of 0.75 Pbit/s optical amplifier repeater transmission (1,200 km) in combination with a multi-level coded modulation system was also shown. In relation to ultra-high capacities, the further pursuit of limits made progress by combining mode-division multiplexing and multi-band transmission technology under conditions that exclude the cladding diameter limit of 250 μm. For a spatial multiplicity (number of modes × number of cores) of 100 or more, the world's first transmission experiment (11.3 km) exceeding 10 Pbit/s (10^{16} bit/s) was reported in 2017[7] and a transmission experiment

(13 km) achieving the world's highest capacity of 22.9 Pbit/s was reported in 2023[8].

Recently, with a view toward implementing SDM technology in the terrestrial optical network, studies have been progressing on 4-core weakly coupled MCF with the same 125-μm standard cladding diameter as that of SMF from the viewpoints of MCF mass production, international standardization, and suppressing inter-core crosstalk. In 2017, as part of NICT commissioned research (#170, #188), a multi-vendor interoperability experiment was conducted applying prototype 4-core fibers manufactured by multiple fiber vendors with common specifications along with multi-core-fiber amplifiers and multi-core connectors, and a 118-Tbit/s optical-amplifier-repeater (3 × 100 km) transmission experiment was reported[9]. Then, using the knowledge gained from those experiments, studies progressed on the design and mass production of 4-core fiber cable with standard cladding diameter toward the terrestrial optical network also as part of NICT commissioned research (#203)[10]. At present, standardization is proceeding at ITU-T including the issuing of SDM technical reports and international standardization is intensifying at IEC in relation to methods of evaluating and measuring multi-core connectors.

Furthermore,, on looking ahead to the implementation of future Pbit/s-class optical transmission systems, there will be a strong need for applying SDM for compact, integrated, and low-power optical network node equipment such as optical transmitters/receivers, optical amplifier repeaters, and optical switching nodes in addition to enhancing spatial efficiency in spatial multiplexing fiber as a transmission medium. For example, looking back at the history of WDM system introduction, about 10 years were needed from the world's first 1-Tbit/s-class WDM transmission demonstration experiment in 1996 to the full-fledged introduction and practical use of an economical 1-Tbit/s-class WDM system based on 10-Gbit/s channels in Japan in 2003 (Figure 1). The reason for this is that progress was made in the development of compact and low-power 10-Gbit/s-class transmitter/receiver equipment and optical switching nodes during this 10-year period due to the evolution of silicon integrated circuit technology and 10-Gbit/s-class optical transmitter/receiver circuit packaging technology and the introduction of multi-degree Reconfigurable Optical Add Drop Multiplexer (ROADM) nodes. Likewise, in the implementation of practical Pbit/s-class SDM systems, the study of compact, integrated, and low-power SDM optical network nodes will be extremely important in achieving economy in operations while extracting suitable performance from an SDM transmission medium such as MCF. In NICT commissioned research (#188, #170), studies focused on optical switching node integration technology based on SDM technology and on compact and low-power optical amplifier repeaters such as cladding-pumped multi-core optical amplifiers toward the realization of SDM photonic nodes with over-Pbit/s-class node throughput. A 3-node experimental network was configured using standard cladding diameter 4-core fiber and integrated wavelength selective optical switching nodes and an experiment demonstrating node throughput over Pbit/s was reported[11].

3. Progress and Future Outlook of Optical Submarine Cables

This section describes the progress made in optical submarine cables, current technologies, and their future outlook based on SDM technology from the viewpoints of space and power limitations unique to this type of cable.

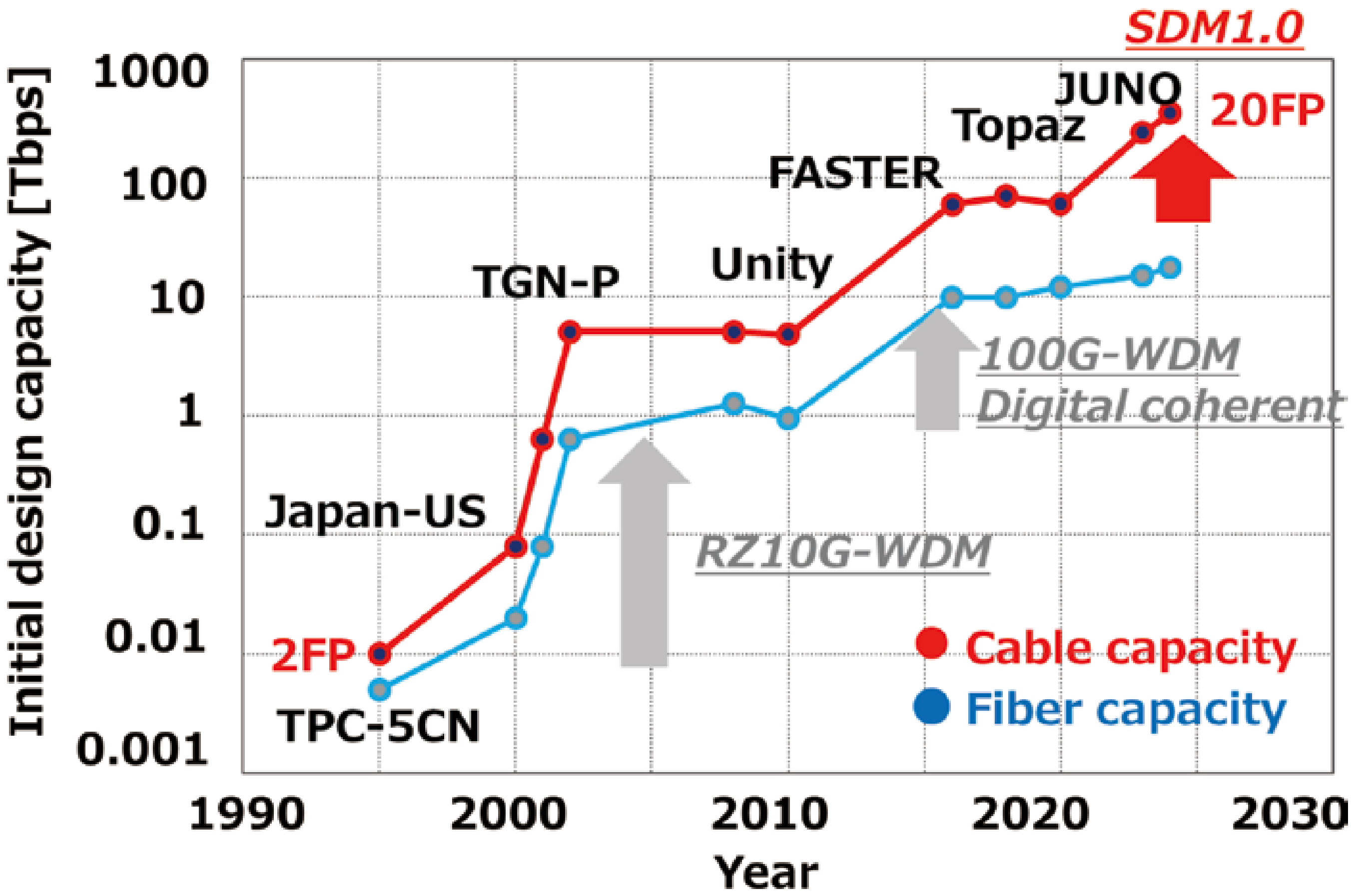
3.1 Change in Capacity per Fiber

Optical submarine cable systems have progressed in the order of parallelization and multi-level modulation through faster data rates of optical signals and bandwidth expansion the same as terrestrial systems. Change over time in fiber capacity and cable capacity of main transpacific optical submarine cables is shown in Figure 2. The signal data rate of 280 Mbit/s for single-wavelength optical submarine cable commercialized in 1989 was increased by approximately 8 times to 5 Gbit/s in the TPC-5 optical amplifier repeater system in 1995. Continuing on, a data rate of 10 Gbit/s and 100 WDM were achieved by expanding the bandwidth of optical amplifiers, applying WDM technology, and applying dispersion-managed soliton transmission technology using chirped Gaussian RZ signals that constitute a steady solution of the dispersion-compensated nonlinear optical transmission line[12]. In this way, total capacity jumped all at once by 200 times to 1 Tbit/s—this system was commercialized globally from the end of the 1990s to the middle of the 2010s[13]. Next, in the digital coherent system, spectral efficiency improved through polarization multiplexing and QAM multi-level modulation, and at present, fiber transmission capacity has expanded by approximately 20 times to 20 Tbit/s.

3.2 Expansion of Cable Capacity by SDM

In commercial optical submarine cables, the capacity that can be transmitted by a single optical fiber is almost saturated, so parallelization by SDM is considered to be an effective approach to expanding capacity by several tens of times as required for next-generation systems. Unlike schemes such as increasing the data rate or modulation level that require more optical power to increase S/N, SDM can expand capacity on the basis of multiplicity. Examining change in cable capacity in Figure 2, it can be seen that the number of fibers and total capacity are increasing from the 2020s on despite the near saturation in fiber capacity. The number of fibers has increased by 10 times from 1995 to the present, and here, SDM technology based on single-core optical fiber is called SDM 1.0. However, due to space limitations in submarine cable with diameters under 2 cm, the number of fibers that can be accommodated in a cable is limited to about 50 (or 25FP = 25

■ Figure 2: Change in fiber capacity and cable capacity of main transpacific optical submarine cables



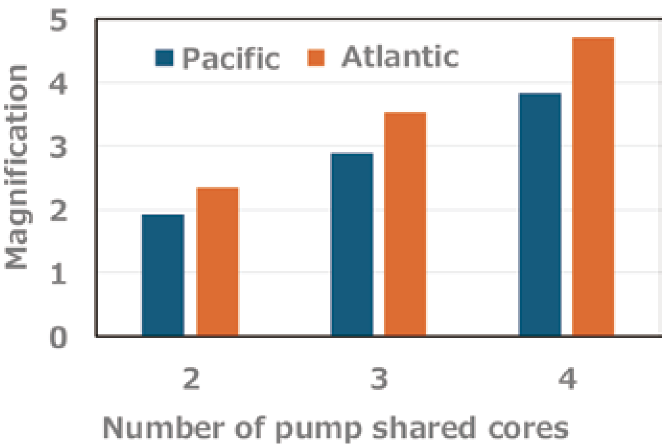
fiber pairs), so research and development is proceeding around the world on SDM 2.0 based on MCF having high spatial efficiency.

The possibility of transoceanic transmission by SDM was first reported in 2012 by a transmission experiment using 7-core fiber and 7-core EDFA[14], and in the following year, the possibility of optical submarine cable exceeding a capacity-distance product of 1-exabit/s × km with a fiber capacity of more than 140 Tbit/s was demonstrated[15]. At present, the research and development of 4-core fiber with a standard cladding diameter of 125 μm[13] and associated standardization activities are actively proceeding, and in the OCEANS project commissioned by the Ministry of Internal Affairs and Communications (MIC) toward early implementation of SDM 2.0 with optical submarine cable, prototype 1.7-cm-diameter optical submarine cable (16FP including 4-core fiber) was fabricated and a 62.9-Tbit/s, 9,150-km transpacific transmission test was conducted[16]. Furthermore, in the TPU transpacific submarine cable system scheduled for commercialization in 2025, the plan is to introduce 2-core fiber, which is part of the results of the OCEANS project, in the Taiwan—submarine branch—Philippines interval of approximately 840 km as the first MCF commercial system.

3.3 Cable Capacity Limitations Accompanying Power Limitations

In addition to space limitations, a limiting condition peculiar to optical submarine cable is power. Since the electrical resistance of the conductor within a submarine cable is approximately 0.8 Ω/km, 8 kV would be lost as heat over 10,000 km assuming a power supply current of 1 A. The electric power of power feeding equipment at a landing station is presently 16–18 kV, and since power excluding the power consumed by cable resistance must be distributed to more than 100 repeaters, it is no exaggeration to say that power limitations determine total system capacity. In SDM 1.0, pump sharing that makes EDFA pump laser diodes (LDs) redundant and excites two EDFAs with one pump LD was introduced so that the number of fibers could be increased while suppressing consumed power. However, further expansion of capacity will require an increase in the number of pump-shared cores. Figure 3 shows the magnification of maximum cable capacity with respect to a reference value versus number of pump-shared cores for transatlantic (7,000 km) and transpacific (9,000 km) systems both using 4-core fibers. The reference capacity used here is 500 Tbit/s (24FP) for the transatlantic optical submarine cable and 350 Tbit/s (20FP) for the transpacific optical submarine cable. Other system parameters include a power supply voltage of 18 kV, power supply current of 1 A, cable resistance of 0.8 Ω/km, and a pump LD voltage of 2.5 V. Span length is increased to 80 km and the number of repeaters is reduced through the use of ultra-low-loss optical fiber (loss α = 0.15 dB/km). With the present number of pump-shared cores, the transatlantic system and transpacific system can achieve a capacity 2.4 times (1.18 Pbit/s) and 1.9 times (670 Tbit/s) the reference capacity, respectively, based on 2-core fiber. It should be noted here that increasing capacity in a transoceanic optical submarine cable is difficult even in the case of 4-core fiber since power limitations prevent the number of effective cores from being increased. As shown in Figure 3, increasing cable capacity here requires that the number of pump-shared cores be increased to 3–4 for 4-core fiber, in which case capacity magnification would be estimated to be 4.7 times (2.4 Pbit/s) for the transatlantic system and 3.8 times (1.3 Pbit/s) for the transpacific system. If the plan is to increase the number of cores even further toward higher capacities through the use of randomly coupled multi-core fiber that is expected to have many cores in the future, fundamental changes will have to be made such as an increase in the power supply and the use of high-voltage-resistant cables and repeaters, so there is a tradeoff between economy and high capacity.

Figure 3: Capacity magnification versus number of pump shared cores in 4-core fiber



4. Conclusion

In this paper, we described the progress made toward higher capacities in the terrestrial and submarine optical transmission systems and the future outlook for ultra-high-capacity systems through spatial multiplexing. Up to now, various types of research and development based on spatial-multiplexing optical transmission technology led by Japan have been actively promoted toward over-petabit-class link capacities beyond the physical limits of existing SMF. With a view to the implementation of high-capacity optical transmission systems using spatial-multiplexing optical transmission technology, the international standardization of 4-core fiber with standard cladding diameter is progressing and the commercial introduction of 2-core fiber for optical submarine cable is scheduled for 2025. Development targets toward "Extremely Advanced Optical Communication Systems" as put forward by the EXAT Study Group established in 2008 have been significantly moved up, and going forward, we can expect ongoing implementation of high-capacity optical transmission infrastructures through more progress in related technologies.

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History of Advancement of SDM-related Simulation: MCF Analysis and Design Technologies

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1. What is MCF?

Research on multi-core fiber (MCF) for space-division multiplexing (SDM) transmission came into full swing when the EXAT Study Group was established in 2008. MCFs are broadly divided into uncoupled-core MCF (UC-MCF) and coupled-core MCF (CC-MCF) in accordance with the distance between core centers (hereinafter referred to as core pitch). In this article, we will refer to UC-MCF as MCF.

MCF is an SDM technology that sufficiently reduces inter-core crosstalk (XT) and uses each core as an independent transmission line. It is classified into homogeneous MCF and heterogeneous MCF. The English names for these MCFs have been decided upon consultation with Professor Masataka Nakazawa and Professor Richard De La Rue[1].

Although MCF essentially has a single mode in each core, it can accommodate multiple modes to expand the spatial multiplexing. These MCFs are either called multi-mode MCF (MM-MCF) or few-mode MCF (FM-MCF).

CC-MCF, on the other hand, utilizes each of the super-modes generated by the arrangement of multiple cores in close proximity as an independent transmission line. When the core pitch is set appropriately, the super-modes are randomly coupled to each other, and the group velocity is averaged to realize an MCF where the group delay spread (GDS) is proportional to the square root of the transmission distance. This type of MCF is called randomly coupled MCF (RC-MCF) and is suitable for long-haul transmission.

Professor Yasuo Kokubun pointed out at the EXAT Symposium held in 2008 that if the core pitch of a two-core fiber is set to about four times the core radius, the propagation constants of the even and odd modes become almost equal, making it easier to couple them[2]. Interestingly, this core pitch is almost the same as the core pitch of RC-MCF, which has been studied extensively since the mid-2010s.

2. MCF analysis and design technologies

Evaluating the properties of fibers initially requires performing an eigenmode analysis to know the propagation constant (eigen value) and the electromagnetic field distribution (eigen function) of each mode. In some cases, the exact solution is known, such as in round core fibers; but when the fiber structure becomes more complex, it becomes difficult to derive the exact solution, requiring numerical analysis. Although there are various numerical solutions, the finite element method (FEM) and beam propagation method (BPM) are often used in the optical frequency range and the finite-difference time-domain method (FDTD) is often used in the radio frequency range. Currently, FEM and BPM are also essential for MCF design, but it is difficult to incorporate bending, twisting, and even random structural fluctuations. For this reason, the coupled-mode theory (CMT) and the coupled-power theory (CPT) have been developed specifically for MCF analysis.

This paper discusses CMT and CPT as MCF analysis and design technologies and outlines the progress of the development of these theories.

3. XT analysis of MCF

CMT has traditionally been used to evaluate coupling between optical waveguides and modes. According to this CMT, XT in MCF is expected to vary periodically in the propagation direction. In 2010, however, it was experimentally shown that XT increases in proportion to the transmission distance[3]. This suggests that the structure is randomly fluctuating in the propagation direction. The introduction of CPT then made it possible to explain this experimental result in 2010[3].

Also, in the same year, measurement of the bending radius dependence of XT in heterogeneous MCF experimentally showed that there is a phase-matching region (PMR) and a non-PMR region (non-PMR) around the bending radius called the critical bending radius[4]. In 2011, a discrete changes model (DCM) was developed to account for random discrete changes in coupling power at phase-matching points (PMPs)[5, 6], and it was found that XT increases with the bending radius in the PMR[5, 6].

Despite its simplicity, DCM cannot be applied to non-PMR without PMP; thus, in 2011, a CMT was developed that takes into account bending, twisting, and random structural fluctuations[7]. As a result, it was found that XT is governed by bending in PMR and by the statistical property of the structural fluctuations (quantified with correlation length) in non-PMR[7].

Since calculation takes a long time in CMT (requires stochastic treatment), a CPT that takes into account not only structural fluctuations but also bending and twisting was developed in 2011[7]. In this case, since the power coupling coefficient (PCC) varies in the propagation direction, the coupled-power equation is solved sequentially.

In 2012, an exponential autocorrelation function (ACF) was introduced to derive a closed-form expression of PCC averaged over the twisting period[8] (with the correlation length as the unknown variable). This analytical model can be applied to both PMR and non-PMR and is widely used for XT analysis of MCF. In the case of MM-MCF and FM-MCF, there is a need to analyze the coupling between modes in the core; thus, a CMT capable of such analysis was developed in 2015[9].

4. GDS analysis of RC-MCF

From the mid-2010s, GDS analysis of RC-MCF came into full swing using CMT, and it was found that GDS is proportional to the square root of the transmission distance (which has been confirmed experimentally).

According to the CMT analysis, GDS is strongly dependent on the core pitch, and the core pitch that results in the minimum GDS is around 20 μm, depending on the degree of twisting and manufacturing variability[10]. This core pitch is almost four times the core radius (core diameter of about 9 μm) of a silica-based single-mode fiber.

5. XT analysis with PMC consideration

In 2011, it was theoretically shown that the XT distribution in MCF without polarization mode coupling (PMC) follows a chi-square distribution with two degrees of freedom, and with PMC, follows a chi-square distribution with four degrees of freedom[5, 6]. Although this XT distribution in MCF has been experimentally confirmed[6], the dependence of XT on the birefringence correlation length and the birefringence beat length has remained undiscussed for some time.

In 2020, XT analysis with CMT was performed with no bending[11] and in 2022 with bending, including heterogeneous MCF[12] (assuming the same correlation length and the same beat length for all cores). Also in 2020, a simple analysis method for XT using polarization mode dispersion coefficient as the unknown variable was developed[13] (under the condition that the correlation length is sufficiently small compared to the beat length).

6. XT analysis of MCF with BSA transmission

There has been a growing interest in bidirectional signal assignment (BSA) transmission, which can significantly reduce XT by placing signal lights with opposite propagation directions in neighboring cores. For long-haul BSA transmission, backscattered XT and indirect XT must be evaluated, and for short-reach BSA transmission, back-reflected XT and indirect XT must be evaluated, and CPT is used for both evaluations[14].

PCC has been implicitly considered to be symmetric, but with core-dependent loss (CDL), PCC becomes asymmetric. In 2023, it was reported that when the ACF is given by an exponential function, treating the PCC as a symmetrical quantity poses no issues within the practical ranges of CDL and correlation length[15].

7. Unresolved issues (Conclusion)

We discussed CMT and CPT as analysis and design technologies for MCF and outlined the development progress of these theories. In conclusion, below are some of the issues that need to be resolved going forward.

In particular, the anomalously large correlation lengths, the cladding-diameter dependence of XT, and the bending-radius dependence of the correlation length cannot be reasonably explained in the framework of CMT or CPT[16] (that could be resolved with a newly derived PCC[17]). Furthermore, the phenomenon where the LP mode, which is theoretically not an eigenmode, propagates as an eigenmode in FM-MCF has not yet been elucidated[16].

Lastly, the author would like to thank all the members of the EXAT Study Group for continued discussions on SDM-related technologies.

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Latest Trends and Future Prospects of SDM Optical Fiber Research

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1. Introduction

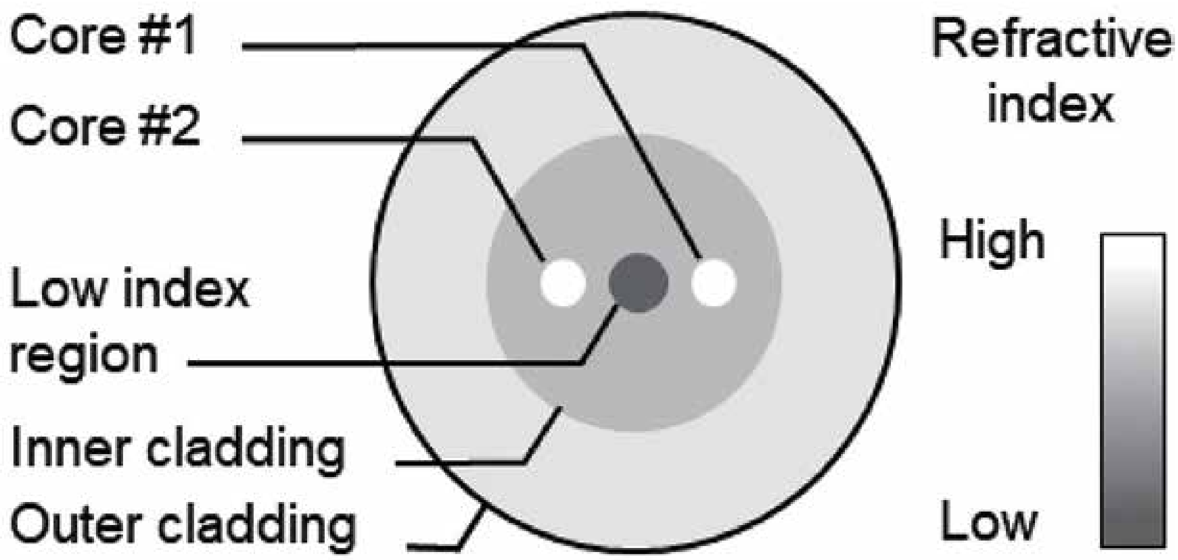
As a result of the development of wavelength division multiplexing and digital coherent transmission technologies against the backdrop of exponential growth in demand for communication capacity in optical communication networks, the per-core information transmission capacity of widely used single-mode fibers (SMFs) is approaching its physical limit, pointing to the increasing importance of spatial division multiplexing (SDM) as a means to further expand transmission capacity. This paper describes the research trends in SDM optical fiber for submarine communications, where the commercialization of SDM optical fibers has begun, and for terrestrial communications, where field verification is progressing toward the widespread use of SDM optical fibers.

2. SDM optical fiber for submarine communications

In submarine cables, which often use advanced transmission technologies, the transmission capacity per core is already nearing its limit. Additionally, under the constraints of power supply to submarine optical repeaters, SDM is effective in maximizing transmission capacity. Therefore, the need for SDM is high[1], and multi-core optical fibers within cables are becoming widespread as the first generation of SDM. As a result of the shift to multiple fibers, 48-fiber cables have been commercialized as cutting-edge optical submarine cables[2]. However, further increase in the number of fibers is likely to be difficult due to the structural limitations of submarine cables. Therefore, multi-core fiber (MCF), which has multiple cores in a single optical fiber, shows promise as the second-generation SDM technology[3]. Activities for its commercialization for submarine communications have in fact progressed. In 2023, two-core fiber (2CF) for optical submarine cables was commercialized[4], and construction of optical submarine cables using 2CF was announced[5].

Since MCFs have multiple cores, complexities not found in SMFs may arise, such as in managing core layouts for connections and in managing crosstalk between cores in installation environments. In addition to the optical properties of the MCF itself, it is also important to reduce the above complexities in order to promote the smooth uptake of MCF. In the 2CF for submarine communications[6,7] (Figure), measures to reduce complexity have been adopted, such as (a) the mirrored symmetric core layout eliminates the need for end-to-end management by eliminating the polarity of the MCF, and (b) core identification by core shift eliminates the need for identification markers. Likewise, optical performance equivalent to that of conventional SMF for submarine communications has been demonstrated.

Figure : Structure of 2CF for submarine communications



3. SDM optical fiber for terrestrial communications

SDM optical fibers such as MCF will be required in the future to expand transmission capacity under the constraints of the conduit space in terrestrial communication networks, where multi-vendor implementation and standardization are also crucial. In this regard, inter-connection between multiple vendors using four-core fiber[8] and documentation of SDM technology[9] for ITU standardization have been carried out.

In 2019, a field test bed for MCF was built for the first time in the city of L'Aquila, Italy[10], which demonstrated transmission performance in a terrestrial environment and verified application technologies leveraging the characteristics of MCF, such as optical frequency clock transmission[11], which uses the correlation of phase fluctuation between cores to improve accuracy. In addition, high-density optical cables have been used for connections within and between data center buildings. In particular, the use of 12-core fiber is expected to increase cable density and reduce connection time per core[12].

4. Conclusion

Development of SDM optical fiber is progressing, along with progress in its commercialization for submarine communications and in its field verification for terrestrial communications. Further growth of optical communication networks is anticipated with the progress in the development and mass production of transmission equipment and related technologies for connection and amplification.

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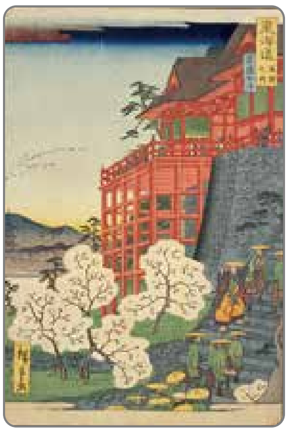
Cover Art



Kiyomizudera Temple, Kyoto, from Famous Views of Tokaido Road

Utagawa Hiroshige (1797-1858)

Source: National Diet Library, NDL Image Bank (https://rnavi.ndl.go.jp/imagebank/)

Recent Trends and Future Challenges concerning Research on Multi-core-Fiber Connection and Optical Cable

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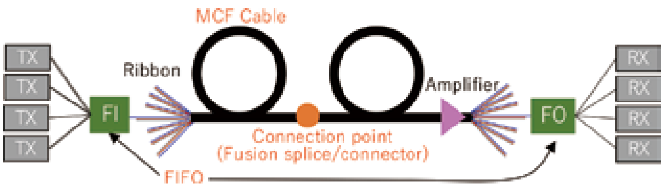
1. Background

The "single-mode fiber" (SMF) currently used in optical communications has only one core, which provides the pathway for transmission of light, and its communication capacity is said to be approaching the limit[1]. To address the growing need for enhanced communication capacity, "multi-core fiber" (MCF) has become the focus of significant attention. Recently, several connection technologies and cable technologies necessary for the practical application of MCF have been reported. The latest trends and future challenges concerning these technologies are introduced in this article.

2. Multi-core-fiber connection technology

A schematic diagram of a transmission system using MCF cables is shown in Figure 1. Firstly, the fusion-splicing technology and connector-connection technology for connecting the MCFs are introduced. Secondly, the SMF-MCF conversion technology required to connect MCF cables to existing SMFs is then introduced. Finally, the challenges associated with these technologies are described.

■ Figure 1: Schematic diagram of MCF transmission system

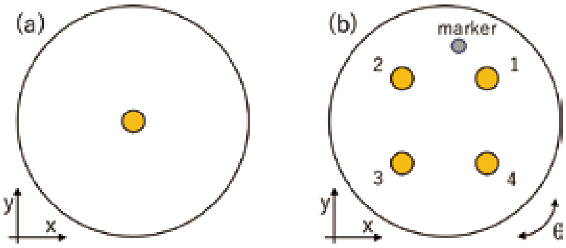


2.1 Fusion-splicing technology

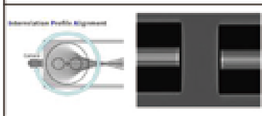
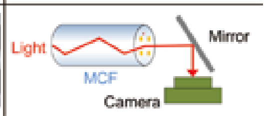
Fusion splicing is a method of joining optical fibers by heating and melting the tips of the optical fibers. It is widely used as a general-purpose method of connecting SMF (with one core in the center of the cladding); however, MCFs (with multiple cores located away from the center of the cladding) must be rotationally aligned around the axis of the MCF (see Figure 2). The two main methods for observing and aligning the cores of MCFs are shown schematically in Figure 3. The "side-view" and "end-view" methods are ways of aligning the cores of MCF in reference to side and cross-sectional images of the MCF, respectively. Compared to the end-view method, the side-view method allows for a simpler equipment configuration and is advantageous in terms of size and cost.

In recent years, many studies have used the side-view method, and it has been reported that the average splice loss and alignment time for 4-core MCF are 0.1 dB and 90 seconds, respectively[2, 3]. The challenge facing MCF fusion-splicing technology is how it can achieve similar splice loss and splicing time as those achieved by SMF splicing technology, and, at present, splice loss and splicing time must be further reduced.

■ Figure 2: Cross-section and alignment direction of optical fiber: (a) SMF and (b) MCF



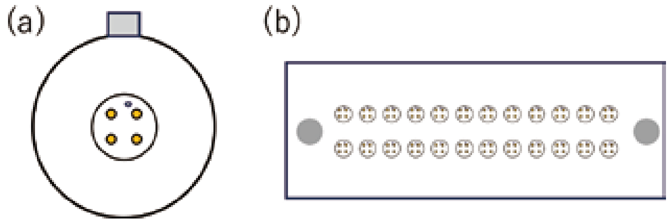
■ Figure 3: Observation methods and features of fusion splicing

	Side-view method	End-view method
Observation methods		
Observation mechanism	Simple (Rotation-alignment mechanism is required)	Complicated
Alignment time	Middle	Long
Detection of markers	Possible (simple structure)	Possible (complicated structure)

2.2 Connector technologies for single fiber and multiple fibers

"Connector connection technology" is a kind of a detachable connection method. As with fusion splicing, after rotationally aligning each MCF core with respect to the axis of the optical fiber, it is necessary to fix the cores to the connector key. To date, as well as single-MCF connectors, multiple-MCF connectors have been reported (see Figure 4). As for single-MCF connectors average loss of less than 0.1 dB has been reported[4], and as for multiple-MCF connectors average loss of less than 0.2 dB has been reported[5, 6].

■ **Figure 4: Schematic diagrams of MCF connectors: (a) single MCF and (b) multi MCF**



The challenge facing MCF connector-connection technology is how it can achieve similar connection loss and alignment time as those achieved by SMF connector-connection technology while minimizing associated costs. Currently, it is necessary to further reduce connection loss and alignment time.

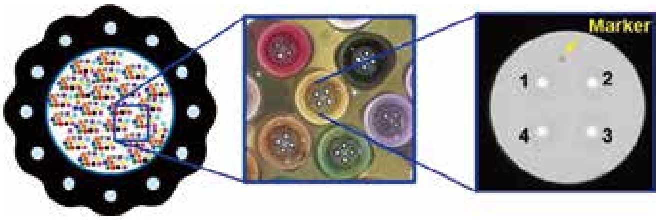
2.3 SMF-MCF conversion technology

Connecting existing SMFs and devices to MCF necessitates a fan-in/fan-out (FIFO) configuration to multiplex and demultiplex each core of the MCF. The four types of FIFO configurations—with the associated insertion loss and cost—are shown schematically in Figure 5. As shown in the figure, the bundle type[7, 8, 9], which achieves low loss and low cost, and the fused type[10], which achieve low loss and high reliability, are attracting attention. Insertion losses averaging 0.4 dB and 0.2 dB have been reported for the bundle and fused types, respectively. The SMF-MCF conversion technology (FIFO configuration) is implemented as a device that is not found in normal SMF systems, and it is hoped that the device will be further reduced in terms of loss, cost, and crosstalk in the future.

3. Multi-core-fiber cable technology

To enable the practical application of MCF, it is necessary to install it in the field as cables. To date, MCF cables consisting of several to several hundred 2- to 12-core MCFs have been reported[11-15]. It has also been reported that these MCF cables have loss increases and mechanical properties equivalent to those of SMF cables[11-14], and it has been confirmed that they do not pose any major problems when laid in the field[13]. A schematic cross-sectional view of a cable composed of 288 four-core MCF and a photo of a portion of the cable are shown in Figure 6. Since MCF cables can bundle a very large number of cores at high density, they are expected to be used in applications requiring high-density, high-capacity transmission, such as undersea cables and data centers. To enable the practical application of MCF, it is desirable to develop technology to reduce the connection time and inspection time for a large number of MCFs in a cable.

■ **Figure 6: Cross-sectional view of MCF cable and MCFs**



4. Conclusion

The latest trends concerning the connection technology and cable technology necessary for practical application of MCF—and future challenges facing each technology—were introduced.

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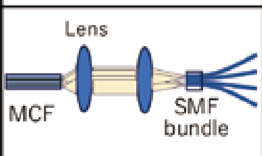
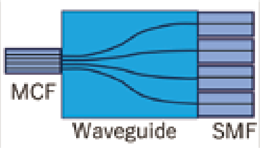
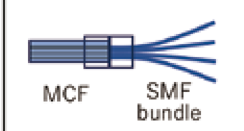
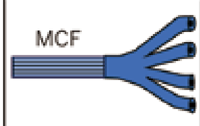
■ **Figure 5: Four types of FIFO configurations**

	Free space type	Waveguide type	Fiber bundle type	Fused type
Schematic diagram				
Loss	Low	Medium	Low	Low
Cost	Medium	Low	Low	Medium

Recent Trends and Future Prospects regarding Multi-core Optical-Fiber-Amplification Technology

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1. Introduction

Single-core erbium-doped fiber amplifiers (EDFAs) are widely used as standard optical fiber amplifiers in optical-fiber communication systems. A multi-core (MC) EDFA is expected to be smaller and consume less power than a single-core EDFA. It can be miniaturized because multi-core optical devices such as MC-EDFs, isolators, and wavelength-division-multiplexing (WDM) filters are almost the same size and have about the same number of components as conventional single-core devices. The mounting volume of a MC-EDFA is almost the same as that of a single-core EDFA, so the volume per core is reduced by approximately the number of cores. The core-pumped 4-core EDFA has been improved in terms of reducing mounting volume and achieving amplification characteristics equivalent to those of a single-core EDFA.

It is expected that only cladding-pumped MC-EDFAs will achieve low power consumption. The reason for that expectation is that the electrical-optical conversion efficiency of a multi-mode laser diode (MM-LD), which is the pump optical source of a cladding-pumped MC-EDFA, is approximately 1.5 times that of a single-mode LD, which is the pump optical source of a core-pumped MC-EDFA. However, the absorption efficiency of the erbium-doped core in regard to the cladding-pump light is extremely low, so improving the efficiency has been attempted. Recently, power consumption per core of a coupled-12-core EDFA (operating in the C-band) reached a lower level than that of a single-core EDFA[1] and power consumption per core of an uncoupled 19-core EDFA (operating in the L-band) reached the same level as that of a single-core EDFA[2].

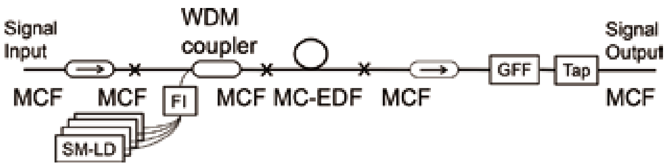
The latest trends and directions of future development of the core-pumped MC-EDFA, which is expected to enable miniaturization, and the cladding-pumped MC-EDFA, which is expected to enable low power consumption, are introduced in this report.

2. Core-pumped MC-EDFA

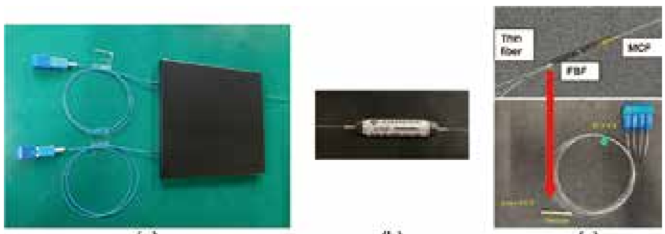
An typical configuration of a core-pumped MC-EDFA is shown in Figure 1. The MC-EDFA is configured so that the input and output fibers are spliced with multi-core fibers (MCF) by a fusion-splicer[3, 4]. Since the number of pump optical sources is the same as the number of cores, power consumption of the MC-EDFA is the same as that of a single-core EDFA. The optical system is configured in the same way as a single-core EDFA, except that MCFs propagate the signal light and the optical device has multi-cores, so the mounting volume is also the same as that of a single-core EDFA. The volume per core is therefore reduced by increasing the number of cores.

A photo of the exterior of the 124 × 135 × 10 (mm^3) housing that houses the optical system (excluding the GFF and tap shown in Figure 1) is shown in Figure 2(a). Two input/output 4-core fibers and four pump input fibers are connected to the housing. The dimensions of the 4-core isolator are f5.5 × 27 mm[5] [Figure 2(b)] and those of the fiber-bundled 4-core fan-in (FI) are 3 × 3.5 × 45 mm^3 [Figure 2(c)][6, 7]. It is clear that the dimensions of 4-core EDFA and optical devices are almost identical to those of the single-core EDFA and optical devices for single cores. A fusion splicer with an automatic-alignment function was used to connect the MCFs. Average splicing losses for two-electrode and three-electrode discharges are 0.07 dB and 0.02 dB, respectively, which are comparable to those for single-core fibers[8-10]. The fusion time, including alignment, for a 4-core fiber with a marker is short (90 s). Although the noise figure (NF) is about 1 to 2 dB larger than that of a single-core EDFA, the gain is the same with a core-to-core gain difference of less than 1 dB. By reducing insertion loss of optical devices, etc., it will be possible to reduce the NF close to that of a single-core EDFA.

■ Figure 1: Typical configuration of core-pumped MC-EDFA: Arrow: isolator; cross: fusion points; GFF: gain-equalizing filter; FI: fan-in



■ Figure 2: (a) Appearance of a core-pumped 4-core EDFA, (b) 4-core isolator, and (c) fiber-bundle fan-in (FI)



3. Cladding-pumped MC-EDFA

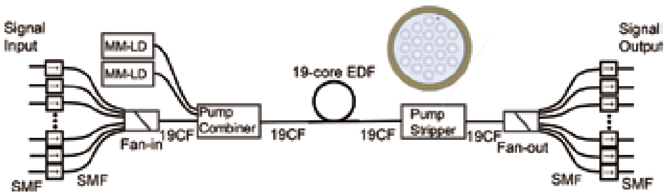
A typical configuration of a cladding-pumped MC-EDFA is shown in Figure 3[2]. To propagate the pumping light in the cladding, a "double-cladding" structure is formed by coating the outside of the glass cladding with a low-refractive-index resin, as shown in the cross-sectional photo of the 19-core EDF shown in Figure 3. The difference between the cladding-pumped MC-EDFA and the core-pumped configuration is that the output light of the MM-LDs is injected into the inner cladding of the MC (19-core)-EDF by using the pump combiner, and the residual pump light from the MC (19-core) fiber is extracted by the pump stripper. If the single-core isolators installed outside the FIFO are replaced with multi-core isolators, the mounting volume is reduced. Amplification characteristics of a C-band cladding-pumped 19-core EDFA are shown in Figure 4[11]. The amplification characteristics are identical to that of a single-core EDFA, and the gain difference between the cores is less than 1 dB. Note that the NF of the C-band cladding-pumped 19-core EDFA is about 1 dB larger than that of the single-core EDFA due to the insertion loss of the optical device.

An issue with cladding-pumped MC-EDFAs is their low efficiency of cladding pumping. The large inner-cladding diameter of MC-EDF cable makes it difficult to calculate light-propagation efficiency and optimize the MC-EDF. We have therefore experimentally identified ways to increase cladding-pumping efficiency[12]. Since the output power of the amplified light is proportional to cladding-pumping power density, the first way is to reduce cladding diameter[13]. The second way is to increase core diameter. Increasing core diameter is considered to improve the probability that the cladding-pumped light collides with the core. The third way is to increase the number of cores[14]. When core characteristics and core density are the same, gain is higher when the number of cores is greater. This way is considered to be highly effective in scattering cladding pump light.

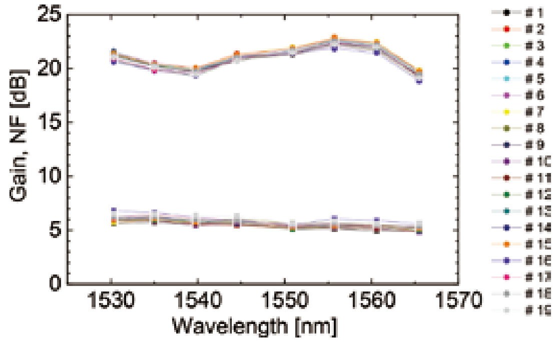
By applying all three ways, we fabricated a 19-core EDFA with cladding diameter of 166 µm, core-to-core distance of 30 µm, and mode-field diameter of 7 µm. When EDF length was set to 8 m, the input optical signal was amplified in the C-band; in particular, under pump power of 28 W and input of –5 dBm/core, output was 17.5 dBm/core[4], which is, however, below the 20 dBm/core required for practical use. On the other hand, when EDF length is set to 50 m, the input signal is amplified in the L-band, and under input of 7.5 dBm/core and pump power of 28 W, output power was increased to 24.3 dBm/core[4].

Output power and power consumption of the developed 19-core EDFA (under cladding pump power of 11.2 W) were respectively 20 dBm/core and 1.2 W/core, which is equivalent to that of a single-core EDFA. We believe that the increased EDF length of the EDFA (50 m) compensates for its low cladding-pumping efficiency.

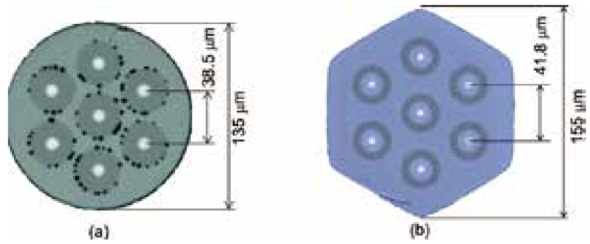
■ Figure 3: Typical configuration of cladding-pumped MC-EDFA. MCF: double-clad fibers; arrow: isolators



■ Figure 4: Typical amplification characteristics of cladding-pumped 19-core EDFA. Input signal power: -5 dBm/core; pump power: 35 W[11]



■ Figure 5: (a) 7-core EDFA with air holes inserted in the cladding[15] and (b) 7-core EDFA with hexagonal cladding[16]



Recently, a 12-core EDFA with smaller cladding diameter (90 µm) and higher core density finally demonstrated lower power consumption than that of a single-core EDFA, even in the C-band, where the EDF length is short[1]. Core-to-core distance of this 12-core EDFA is reduced to 15.5 µm, so it operates as a coupled MC-EDFA. The remaining challenge is to improve gain under C-band operation of uncoupled MC-EDFAs, which require core-to-core distance of, for example, 30 µm or more.

Furthermore, it has been confirmed that inserting air bubbles (as "Mie scatterers") in the cladding[15] and changing the cladding shape from circular to hexagonal[16], for example, are effective means to improve cladding-pump efficiency. Such means would help reduce power consumption of cladding-excited MC-EDFAs.

4. Conclusion

The latest trends and future directions of technologies concerning core-pumped MC-EDFAs and cladding-pumped MC-EDFAs, which are expected to be smaller and achieve lower power consumption, respectively, were introduced.

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Activities concerning the EXAT Roadmap and Trends in Standardization of SDM Optical Fiber

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1. Introduction

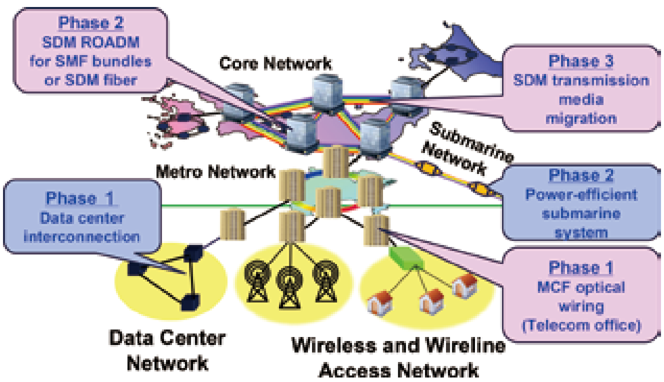
The Ad Hoc Technical Committee on Rapid Advancement of Optical Communication Infrastructure Extremely Advanced Transmission Technologies (EXAT) was the world's first body to advocate the importance of the "3M" technologies: multi-core, multi-mode, and multi-level modulation. As a guidepost for the future innovation of optical communication infrastructure using 3M technologies, the first and second editions of the (EXAT) Roadmap were respectively published in 2017 and 2020[1]. In this report, first, the relationship between the EXAT roadmap and current trends in space division multiplexing (SDM) technology is reviewed and, second, trends in international standardization of SDM optical fiber are outlined.

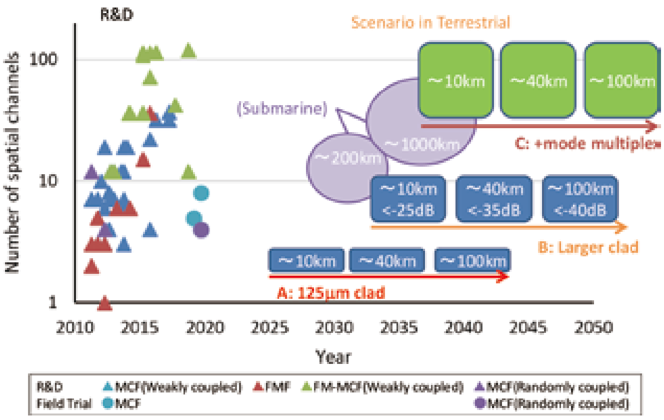
2. EXAT Roadmap

The objectives of the EXAT roadmap are twofold: (i) promote networking among researchers related to 3M technologies and (ii) share the technology roadmap and efficiently deploy EXAT. Since 2010, research on SDM technology, including 3M technology, has been active worldwide[2], and the first objective of the EXAT roadmap has been fully achieved. Hereafter, the relationship between the deployment scenarios of SDM technology envisioned by the EXAT roadmap for 2017 to 2020 and associated current trends are examined. The three deployment phases of SDM technology as envisioned in the EXAT roadmap are shown schematically in Figure 1. In the first phase, SDM technology will be applied for optical wiring between data centers and within telecommunication stations; in the second phase, it will be applied for submarine systems and terrestrial trunk networks; in the third phase, the transition to SDM optical fiber will proceed in a variety of areas. Scenarios for deployment of SDM optical fiber envisioned in the EXAT roadmap are depicted graphically in Figure 2. According to Figure 2, the expansion of spatial multiplexing is expected to continue in three phases: (A) maintaining the standard cladding diameter, (B) switching to increased cladding diameter, and (C) applying spatial modes. It is expected that SDM optical fiber with standard cladding diameter will be deployed in short-haul sections of terrestrial trunk networks from the late 2020s and in submarine systems from the early 2030s.

Although SDM optical fiber has not been commercially deployed as of April 2024, Google announced plans to apply multi-core fiber (MCF) in some new submarine systems[3] in September 2023. Moreover, also in 2023, Sumitomo Electric Industries, Ltd. announced the productization of 2-core structured MCF[4]. According to Google's plan, they will consider applying two-core MCF while keeping the standard cladding diameter in a manner that is consistent with the image of expanded spatial multiplexing shown in Figure 2. On the contrary, while it is assumed in Figures 1 and 2 that SDM technology will be deployed for short-haul sections of terrestrial trunk networks, currently, it is first being deployed in undersea systems, which were considered the second-phase deployment area. This situation is thought to be due to the fact that the space for accommodating optical fibers in currently used submarine optical cables only allows fibers with diameter of a few millimeters, and increasing capacity by increasing the number of accommodated cores is already reaching its limit. In other words, space constraints are becoming apparent in the case of submarine systems. An important related issue is what technologies will be required to expand the scope of application of SDM technology to terrestrial systems and further accelerate the introduction of undersea SDM systems. The EXAT roadmap also suggests a direction for answering the question of what technologies will be required to expand the application scope of SDM technology. As for the short-distance applications of SDM technology envisioned in the first phase, bulk connection of multi-core optical fibers will be essential to efficiently operate a huge number of cores or spatial channels. Moreover, the widespread use of undersea SDM systems requires the implementation of SDM optical amplifiers with higher efficiency than that of existing single-core optical amplifiers in parallel use. Therefore, we believe that by referring

Figure 1: Three anticipated phases of implementation of SDM technology[1]





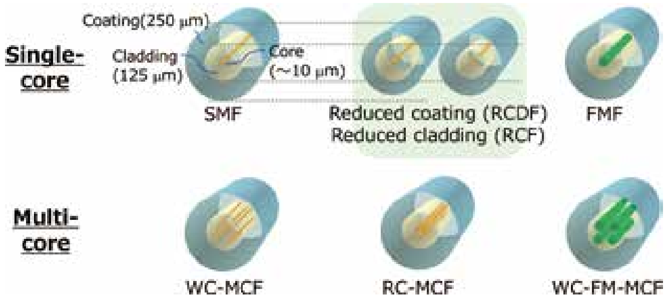
■ **Figure 2: Roadmap for implementing SDM optical fiber[1]**

to the existing EXAT roadmap and clarifying the technologies that will be implemented in the near future, it will be possible to accelerate the deployment of SDM technology.

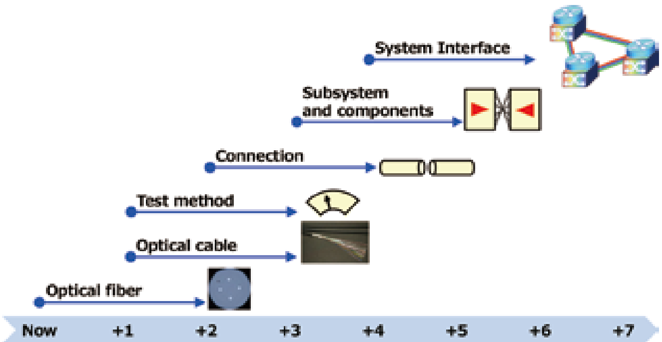
3. Standardization activities concerning SDM optical fiber

Today's international standards for optical-fiber cables and optical-connection technologies are established and revised through the collaborative efforts of the International Telecommunication Union, Telecommunication Standardization Sector (ITU-T) and the International Electrotechnical Committee (IEC). Discussions regarding MCF optical connectors are already underway within the IEC, and standard documents for test methods and optical compatibility have been established[5, 6]. As for SDM optical fiber, on the contrary, in 2022, the ITU-T will issue a new technical report summarizing the technical trends concerning SDM optical-fiber cables and the issues toward their standardization[7], and it will define six types of optical fiber as candidates for SDM optical fiber, as shown in Figure 3. Meanwhile, in accordance with a proposal from Japan, at the meeting in November 2023, it was agreed to discuss establishing a new SDM-optical-fiber recommendation after clarifying the areas and timing of application of the various types of SDM optical fibers shown in Figure 3. For that reason, it is expected that discussions toward standardization of SDM optical fibers will progress in the future; however, it is important to note that it will be essential to establish an SDM ecosystem, including related technical standards, to create the conditions in which SDM transmission systems can be widely used.

An illustration of the roadmap for implementing the SDM ecosystem is shown in Figure 4. As shown in the figure, even if we limit ourselves to technical standards for the physical layer when building the SDM ecosystem, it will be necessary to define standards for not only optical fiber but also optical cables, test methods, connection technologies, subsystems and optical components, and system interfaces. Even under the assumption that each standard requires at least two years of discussion and that related technology fields are examined in parallel, it will still take approximately six years to establish all the standards. If the goal is to implement terrestrial SDM transmission systems widely in the early 2030s, it is thus necessary to begin formulating SDM-optical-fiber standards from around 2025 and to promote planned standardization through close cooperation between the ITU-T and IEC.



■ **Figure 3: Six types of SDM optical fibers defined in the ITU-T technical report[7]**



■ **Figure 4: Standardization roadmap for implementing the SDM ecosystem**

4. Conclusion

The relationship between the EXAT roadmap and the current state of SDM technology, as well as trends in international standardization of SDM technology, were outlined in this report. As deployment of standard-cladding-diameter MCF is expected, it is hoped that systematic international-standardization activities will be promoted toward the implementation of an SDM ecosystem, which will focus on deployment of SDM transmission systems in various fields in the early 2030s.

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Latest Trends and Future Outlook of SDM Optical Transmission Technology

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1. SDM Optical Transmission Technology

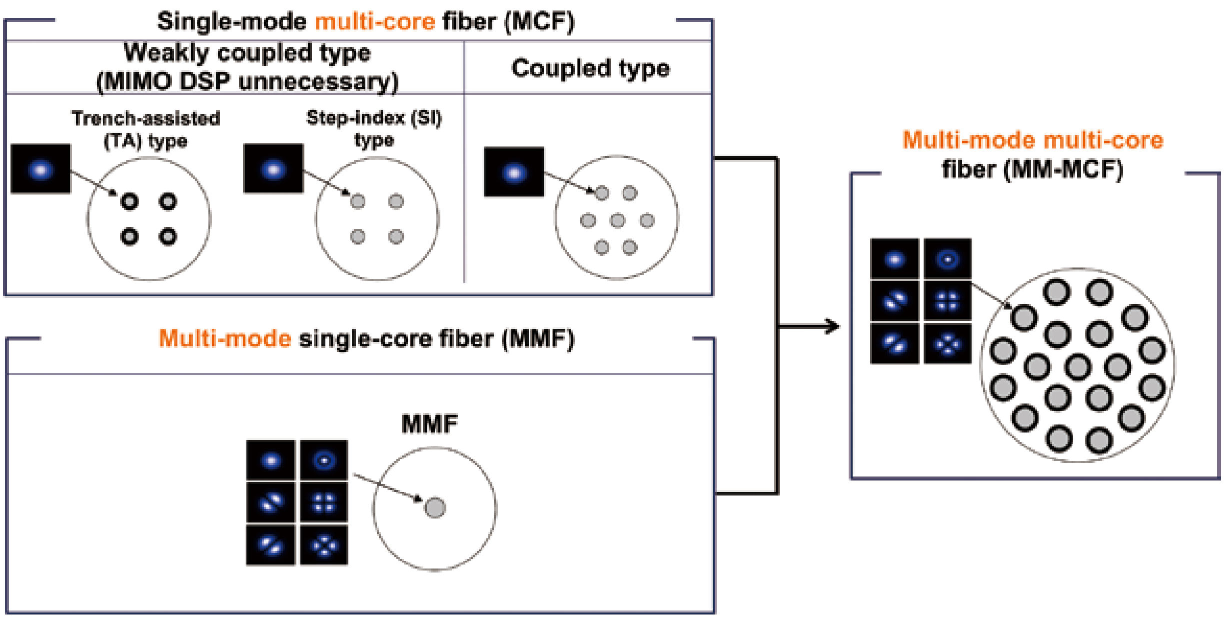
Space-division-multiplexing (SDM) optical transmission systems are being studied to achieve dramatically higher capacities in optical transmission systems. As shown in Figure 1, there are two main categories of optical fiber for SDM: multi-core fiber (MCF) having multiple cores and multi-mode fiber (MMF) having multiple propagation modes.

Additionally, MCF is divided into weakly coupled MCF and coupled MCF according to the degree of inter-core crosstalk. Weakly coupled MCF suppresses crosstalk by designing the refractive index across the fiber cross-section. This type of MCF can be used with conventional optical transmitters and receivers. Furthermore, in terms of the design of weakly coupled MCF, there is the step index (SI) type that holds costs down by using a simple refractive index distribution and the trench-assisted (TA) type that forms a trench layer with a low refractive index around each core to strongly confine light and reduce crosstalk[1]. The number of cores that can be achieved in weakly coupled MCF is limited due to such crosstalk. In long-haul transmission, the upper limit is considered to be four cores in the case of a cladding diameter of 125 μm (standard diameter) the same as conventional single-mode optical fiber (SMF).

There are also coupled MCF and MMF as optical fiber for increasing space-division multiplicity. Both of these types of optical fiber allow for crosstalk between cores or propagation modes to increase space-division multiplicity. The generated crosstalk is removed by large-scale multi-input multi-output digital signal processing (MIMO DSP) installed in the receiver. In coupled MCF, space-division multiplicity at present is inferior to that of MMF, but propagation loss is low and inter-core deviation is small, so coupled MCF is expected to be mainly applied to long-haul transmission systems of 1,000 km or longer (terrestrial or submarine cables)[2]. On the other hand, MMF is being studied as a means of further increasing space-division multiplicity mainly in short- to medium-haul transmission systems up to 1,000 km (between data centers or in terrestrial links). In either coupled MCF or MMF, the implementation of large-scale MIMO DSP according to space-division multiplicity is a major issue.

To increase space-division multiplicity even further, there is also multi-mode multi-core fiber (MM-MCF) as a hybrid structure combining MCF and MMF. Transmission experiments exceeding 10 cores × 10 modes = 100 SDM have been reported[3, 4].

Figure 1: Categories of optical fiber for SDM transmission



2. Trends in Record High-capacity, Long-haul SDM Optical Transmission Experiments

A 138.9 Tb/s, 12,345 km transmission experiment using standard-diameter TA-4 core fiber has been reported as a high-capacity, long-haul transmission experiment using weakly coupled MCF[5]. To increase capacity, this experiment used the L-band and S-band wavelength bands in addition to the existing C-band. A 2.15 Pb/s, 31 km transmission experiment using TA-22-core fiber has also been reported as a high-capacity transmission experiment with many cores[6]. However, in many-core weakly coupled MCF, inter-core spacing must be kept above a certain value to suppress crosstalk, so in general, the fiber will not be of a standard diameter. Fiber with a large diameter can easily break, which means that there are issues here in terms of mechanical reliability[1]. Recently, with the aim of achieving early deployment, there has been much study on the extent to which a high-capacity, long-haul weakly coupled MCF transmission system can be achieved within the standard-diameter constraint[1]. This effort regarding standard-diameter weakly coupled MCF will be described later.

In studies of coupled MCF for increasing space-division multiplicity, there is standard-diameter coupled 19-core fiber as the maximum number of cores and 1.7 Pb/s, 63.5 km transmission has been reported with this fiber[7]. A 1.2 Tb/s, 7,280 km transmission experiment using coupled 12-core fiber has also been reported as a many-core, long-haul transmission experiment exploiting the features of coupled MCF[8]. In addition, a 50.4 Tb/s, 9,150 km transmission experiment using coupled 4-core fiber has been reported as a transmission experiment achieving both high-capacity and long-haul characteristics based on existing wavelength-division multiplexing (WDM) technology[9]. In the above ways, coupled MCF has characteristics applicable to long-haul transmission with small wavelength dependence while having broadband features, so it is expected to be applicable to terrestrial and submarine cable transmission systems that require high capacity and long-haul transmission. In addition, as a high-capacity transmission experiment using MMF, a 3.56 Pb/s transmission experiment using standard-diameter 55-mode fiber exceeding the data rate of coupled MCF with the maximum number of cores (19) has been reported[10]. Furthermore, 15-mode 273.6 Tb/s, 1,001 km transmission has been reported as a many-mode, long-haul transmission experiment[11].

However, in these reports on transmission experiments using coupled MCF and MMF, while using standard-diameter optical fiber, the fact that MIMO DSP can only be performed offline is a major issue.

As for MM-MCF combining MMF and MCF, the first 10-Pb/s ultra-high-capacity transmission experiment using 6-mode/19-core fiber for a space-division multiplicity greater than 100 (6 modes × 19 cores = 114 SDM) was reported in 2017[3], and a 22.9-Pb/s ultra-high-capacity transmission experiment based on expansion of the WDM wavelength band was reported in 2023[4]. However, since MM-MCF is not a standard-diameter type of fiber while also requiring MIMO DSP, it is considered to be a future technology for SDM transmission systems.

3. Initiatives toward Deployment of SDM Optical Transmission Systems

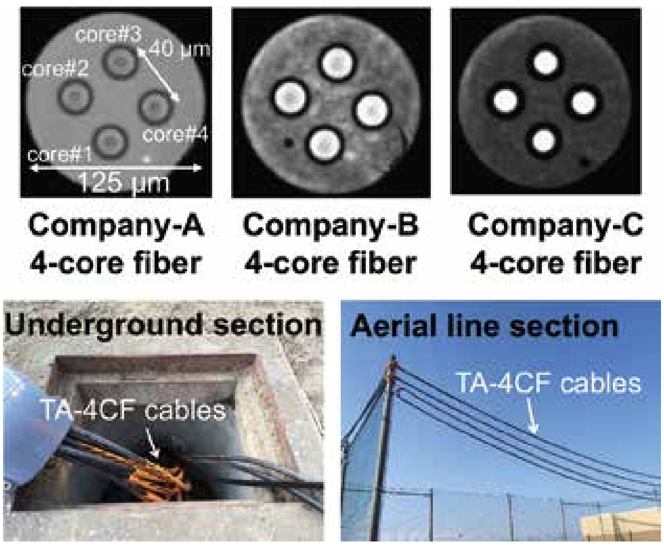
3.1 Standard-diameter SDM Optical Fiber/Cable

Standard-diameter weakly coupled MCF requiring no MIMO DSP and having high mechanical reliability is considered to be a promising technology for early deployment of SDM transmission systems. As a specific transmission application, the making of standard-diameter 4-core fiber into a cable with a view to terrestrial and submarine cable deployment has been reported, and it has been confirmed that there are no significant degradation of optical characteristics (caused by crosstalk, etc.) even in cable form[1, 12]. In addition, adopting a bidirectional core multiplexing transmission system that changes the direction of propagation between adjacent cores would make it possible to suppress crosstalk even further and extend transmission distance[13]. In 2023, Google announced the introduction of standard-diameter weakly coupled 2-core fiber in submarine cable[14].

3.2 Demonstrations in Cable Deployed Environments

Terrestrial transmission systems, in particular, include deployed environments containing much disturbance such as aerial line sections different from laboratory experiments. There are also many connections using splicing or connectors, so demonstrations of transmission performance in actual deployed environments are essential. In the city of L'Aquila, Italy, an evaluation was performed of polarization change speed and propagation delay fluctuations using standard-diameter weakly coupled 4-core fiber deployed in an underground tunnel in a metropolitan area[15]. In Japan, meanwhile, a transmission

■ **Figure 2: Examples of weakly coupled 4-core-fiber cables deployed outdoors**



experiment using standard-diameter 4-core fiber deployed in an underground cable tunnel was reported[1]. Similarly, from KDDI as well, an experiment using standard-diameter 4-core fiber in a nearly real environment was reported[16]. This experiment was performed in a disturbance-containing environment that included aerial lines, manholes, etc. and included interconnection loss between fibers from different vendors[16]. Photographs of 4-core-fiber cross-sections and cable deployed environments are shown in Figure 2. It was shown by this experiment that high-capacity and long-haul transmission at 63.5 Tb/s and 1,800 km could be achieved even when taking interconnection loss and increase in crosstalk into account.

4. Future Outlook for SDM Transmission Systems

4.1 Real-time MIMO DSP for Increasing Space-division Multiplicity

The maximum number of cores in standard-diameter weakly coupled MCF is limited due to crosstalk. To further increase space-division multiplicity, coupled MCF and MMF transmission technologies that assume removal of crosstalk by MIMO DSP are indispensable. It is therefore necessary to develop real-time MIMO DSP in the form of an application-specific integrated circuit (ASIC). In contrast to offline operations, real-time implementation must consider computational delays arising from large-scale MIMO calculations. Given the existence of such delay, a major study item here is whether real-time MIMO DSP can track the moment-by-moment changes in the coupling state between cores and between modes. In recent years, there have been implementations of real-time MIMO DSP using field-programmable gate arrays (FPGAs) and real-time transmission experiments. In 2015, a real-time transmission experiment using 60-km coupled 3-core fiber was reported for the first time[17], and in 2021, 7,200-km long-haul real-time transmission using coupled 4-core fiber was demonstrated[18]. The FPGA board implementing real-time MIMO DSP for coupled 4-core fiber in the latter experiment is shown in Figure 3. These were laboratory experiments, but a demonstration of tracking performance with respect to fiber laid in a harsher environment has been reported[15]. That experiment demonstrated tracking performance using coupled 4-core fiber deployed in the city of L'Aquila, Italy. Although change in the inter-core coupling state here was faster than that of interpolarization coupling in conventional SMF, it was shown that this speed of change fell into a range that could be tracked by MIMO DSP. In 2024, a specific ASIC design was reported for the first time[19]. Going forward, we can expect the deployment of high-capacity SDM transmission systems using coupled MCF and other technologies based on the development of MIMO DSP ASIC devices.

5. Conclusion

In this paper, we introduced record-setting high-capacity and long-haul SDM optical transmission experiments toward higher capacities. We also described demonstration experiments of standard-diameter weakly coupled MCF technology that shows promise for early deployment. Finally, we introduced the latest achievements in real-time DSP as the key to realizing MIMO-DSP-assisted high-capacity optical transmission technology for overcoming the upper limit in number of cores in weakly coupled MCF.

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■ **Figure 3: Real-time MIMO DSP for coupled 4-core fiber**

Application of Core-Selective Switches to a Submarine MCF Branching Unit

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1. Introduction

Space-division multiplexing (SDM) technology is expected to be first implemented in submarine optical-cable systems. As for a new branching unit (BU) architecture for the next-generation submarine SDM era utilizing multi-core fiber (MCF), we have previously proposed a core selective switch (CSS)-based BU architecture that directly supports MCF and can branch on a core-by-core basis without fan-in (FI)/fan-out (FO) devices[1]. This BU architecture can accommodate multiple 1 × 2 fiber switch functions within a single free-space optical system, so it achieves excellent space-utilization efficiency.

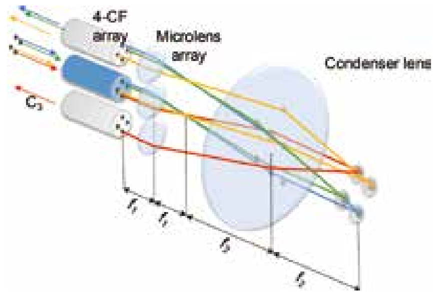
A 1 × 2 CSS optical system using a 4-core-fiber (4-CF) array is shown in Figure 1. The light beams emitted from each core of the input MCF are spatially separated by a microlens array, and they are focused by a condenser lens onto a switching mirror (one of four) corresponding to each core. Each light beam imaged on each mirror is reflected, collimated by the condenser lens and the microlens lens, and focused onto the core of one of the output MCFs with the same local core number. By adjusting the angle of each switching mirror, it is possible to output a light beam to any desired output MCF.

Since the space in a submarine BU is limited and long-term reliability is required, it is necessary to further miniaturize a submarine BU and improve its reliability so that it can practically and directly accommodate 4-CFs. Recently, we reported a submarine SDM BU comprising integrated MCF splitters and integrated CSSs. In this BU, the CSS placed on the input side in the conventional BU is replaced by a passive (and thus more reliable) all-port flipped MCF splitter[2].

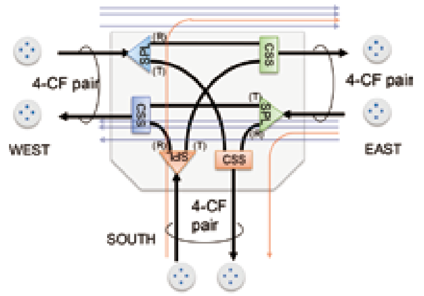
2. Configuration of broadcast- and select-type BU

A BU architecture using a "broadcast and select" (B&S) configuration based on a 1 × 2 all-port-flipped 4-CF splitter and a 1 × 2 4-CF CSS is shown in Figure 2. As a passive component, the all-port-flipped splitter is expected to reduce manufacturing costs and improve reliability. Note that when a 1 × 2 4-CF splitter is configured simply by using a half-mirror in a free-space optical system, the core position of the output light at the reflection port with respect to the direction of light travel is horizontally flipped from the incident core position. Moreover, a similar mirror inversion of core position occurs in the CSS using MEMS mirrors as switching elements; as a result, the inversion of the output CSS

■ **Figure 1: 1×2 4-CF CSS optical system**



■ **Figure 2: BU architecture in B&S configuration**



is automatically canceled at the reflection port of the splitter, and the core position does not invert between the input and output ports of the BU. However, the output light is not reflected by the mirror at the transmission port of each 1×2 4-CF splitter, so the core position from which the output light is output is not flipped horizontally, and the mirror-surface inversion caused by the output CSS is not canceled. In other words, whether core positions are flipped or non-flipped depends to the output port of the BU. To prevent incorrect connection of transmission lines throughout the entire network, it is preferable to prevent a mixture of flipped and non-flipped core positions in the BU. An all-port flipped splitter was therefore used. As for the operation of the splitter, as shown at the top of Figure 3, the light transmitted through the half mirror is sent to a total reflection mirror via relay optics, and the core position of the transmission port from which the output light was transmitted is intentionally flipped.

3. Integrated splitter and integrated CSS prototypes

As mentioned above, space is a precious and finite resource in submarine BUs, which must be as compact as possible. In general, free-space optics can process multiple beams in parallel, and that capability is advantageous for integrating multiple optical systems into a single module. Given that fact, we fabricated three integrated all-port-flipped splitters and three integrated CSSs using a free-space optical system as shown in Figure 3.

The three integrated 1 × 2 4-CF CSSs shown at the bottom of Figure 3 were adapted from three bundled 1 × 8 5-CF CSS prototypes reported in [3], of which only two of the eight output ports were used (the middle core of the five cores is not used). The left side of Figure 3 shows an enlarged image of a 5-CF bundle with three 5-CFs arranged adjacent to each other (at the vertices of an equilateral triangle) with a fiber spacing of 12.5 µm (upper image) and a MEMS mirror array (lower image). The 5-CF bundle was constructed by forming three 125-µm-diameter holes on a silicon substrate and inserting 125-µm-diameter clad 5-CFs into the holes while adjusting the rotational position of the cores. The three integrated 1 × 2 all-port-flipped 4-CF splitters (left photo) and the three integrated 1 × 2 4-CF CSSs (right photo) are shown in Figure 4.

4. Performance of BU prototype

The performance of the BU prototype, comprising the integrated splitters and integrated CSSs, was evaluated using the experimental configuration shown in Figure 5(a). A dual-polarization quadrature-phase-shift-keying (DP-QPSK) 100-Gb/s signal was combined with eight dummy wavelength channels on a 200-GHz frequency grid to form a wavelength-division-multiplexed (WDM) signal in the C-band. Four copies of the WDM signal created by a 1×2 splitter were spatially multiplexed with a 4-CF fan-in device and input into the 4-CF 1×2 all-port-flipped splitter at the south port of the BU. The output port of the 4-CF 1×2 CSS and the input port of the 4-CF 1×2 all-port-flipped splitter at the west (W) and east (E) ports of the BU were connected to emulate three cascaded BUs as visualized in Figure 5(b).

If all CSSs are set up so that all cores of the output ports select the input port to which the reflection port of the splitter is connected, an SDM signal equivalent to a signal that has passed through three BUs clockwise is output from the output port of the south (S) CSS. The accumulated XT of the clockwise path is less than dB, as shown in Figure 6(a), so no measurable optical-signal-to-noise ratio (OSNR) penalty is imposed on the bit-error-rate (BER) performance, as shown in Figure 6(b).

5. Conclusion

As an application of CSSs, a 4-CF BU prototype, comprising three integrated all-port-flipped splitters and three integrated CSSs, demonstrated that SDM signals can pass through three BUs without any OSNR penalty.

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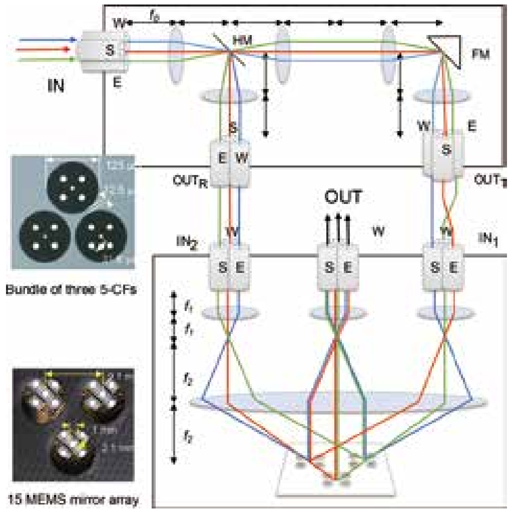
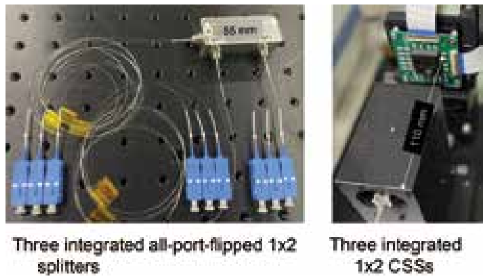
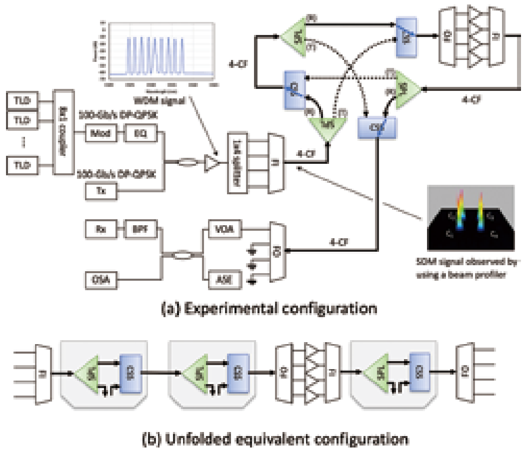
■ Figure 3: BU optical system using splitters and CSSs



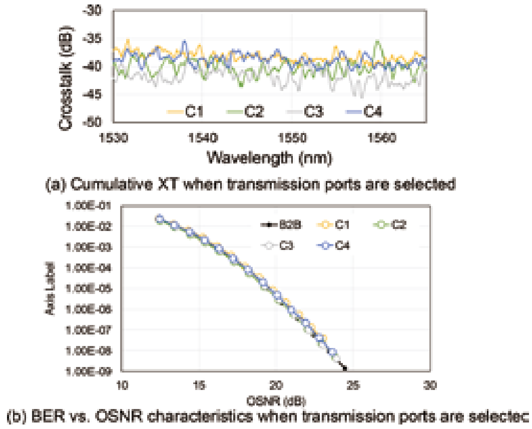
■ Figure 4: All-port-flipped splitters and CSSs



■ Figure 5: Experimental configuration to verify BU prototype performance



■ Figure 6: XT and BER of clockwise path



Connection Characteristics of Coupled Multi-core-Fiber Connectors

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1. Introduction

Currently, single-mode fiber (SMF) is mainly used for optical-fiber communications, and it has become clear that the transmission capacity of a single SMF has reached its limit, namely, 100 Tbit/s. To attain greater capacity than that limit, “space division multiplexing” (SDM) using multi-core fiber (MCF), which has multiple cores in a single optical fiber, is attracting attention. MCF currently being researched can be broadly classified as two types: “uncoupled multi-core fiber” (UC-MCF), in which each core acts as an independent transmission path, and “coupled multi-core fiber” (C-MCF), in which optical signals on adjacent cores are coupled and transmitted in multimode. C-MCF is more suitable for long-distance signal transmission than UC-MCF.

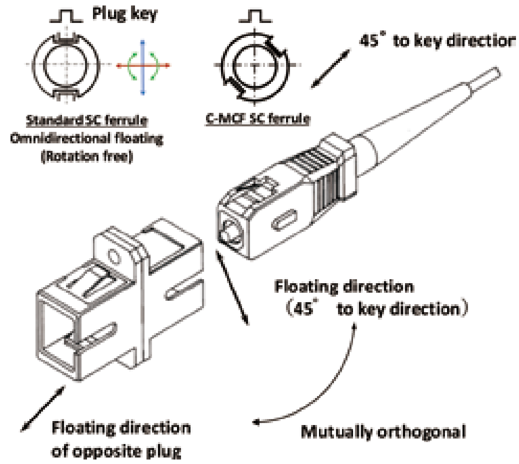
When MCF is used as a transmission line, however, optical connectors that can be detached and connected are required. We previously developed an SC-type optical connector to connect UC-MCFs and confirmed that it has sufficient performance for practical use[1]. However, the connection characteristics of C-MCF connectors have not been reported. In this study, we used a random-mated connectors specified by the International Electrotechnical Commission (IEC) to measure the attenuation of an SC-type C-MCF connector. We then compared the measured attenuation with our previously reported simulation results[2] that show the relation between lateral misalignment and attenuation determined by electromagnetic-field analysis of a C-MCF connector.

2. Structure of SC-type MCF connector

Since optical connectors are usually used to connect optical fiber cables, it is necessary to consider the possibility that an external force of several dozen newtons may act on the optical cable. When such a force interacts with the optical connector, the plug housing can deform by more than 10 μm, which by far exceeds the alignment tolerance of SMF. To solve this problem, a floating mechanism, which offers tolerance between the ferrule and the plug housing, is widely used. Unlike SMF, MCF has cores located away from the center of the fiber, so angular precision around the ferrule axis is required when connecting MCFs. However, angular precision and the ferrule-float structure are mutually contradictory requirements. To solve that contradiction, an SC-type MCF connector with an Oldham’s coupling mechanism was proposed[3]. SC-type MCF connectors have sufficient mechanical performance for use in communication networks; namely, they satisfy transmission tests under tensile load such as IEC 61300-3-51[4].

The structure of an SC-type MCF connector is shown in Figure 1. The ferrule of the connector “floats” in all directions; that is, it rotates freely inside the plug housing. On the other hand, the MCF ferrule has a narrower keyway, so it floats in one direction only, and its rotation is restricted. In the case of C-MCF, as shown in Figure 1, the ferrule is designed to float at 45° from the key direction in a manner that creates a structure that forms an Oldham’s coupling mechanism when the plug is placed opposite the ferrule.

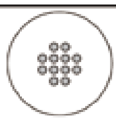
■ **Figure 1**



3. Results of experiment

We attempted to measure the attenuation that occurs when some of the transmitted light leaks from a connection point and thereby reduces optical power at that point of the optical fiber. Since optical signals on separate cores in a C-MCF are combined, it is not possible to measure the attenuation of each core as in the case of UC-MCF. In this study, we measured attenuation of random-mated connectors (according to IEC 61300-3-34) by using a coupled 12-core fiber (C-12CF) with a specification as listed in Table 1. As for the measurements, we evaluated the connection characteristics for all combinations of ten master optical connectors and nine optical connectors connected to the masters. For the measurements, ten C-12CFs with SC-type

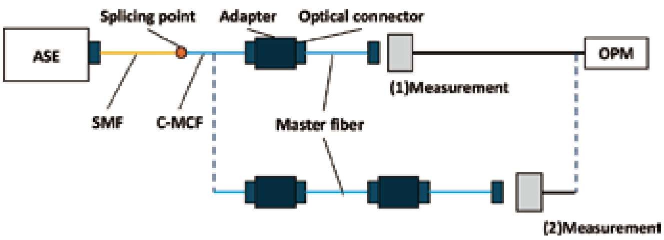
■ Table

Parameter	C-12CF
Cross section	
Core material	S_iO_2
Cladding OD	125 µm
Core radius	4.8 µm
Core pitch	15.5 µm
Core Δ	−0.35 %

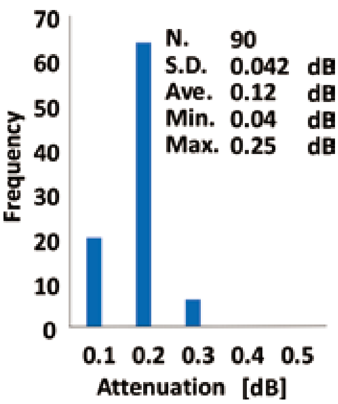
optical connectors on both ends were fabricated, and an ASE light source (wavelength of 1520 to 1570 nm) was used. The setup used for measuring attenuation of the random-mated connectors is shown schematically in Figure 2. For the optical-connector plug, an SC-type optical connector[3] for C-MCF, with an Oldham coupling mechanism as described in Section 2, was used.

Measured attenuation of the C-12CF connector is shown in Figure 3. As for 90 measured connection points, average, minimum, and maximum attenuation were respectively 0.12 dB, 0.04 dB, and 0.25 dB. These results satisfy Grade B (97% less than 0.25 dB) of the optical interface standard for optical connectors (IEC 61755-1). However, as shown in Figure 4, the dominant factor in attenuation is lateral misalignment. According to the simulation results for attenuation of C-12CF shown in Figure 5[2], estimated lateral misalignment of the C-12CF connectors is 0.4 to 1.4 µm. Compared to SMFs, C-MCFs have higher bending loss[5], so changes in the arrangement of the measurement setup can cause fluctuations in optical power, and as shown in Figure 5, changes in mode can cause changes in attenuation. It is therefore necessary to continue studying methods for accurately measuring attenuation.

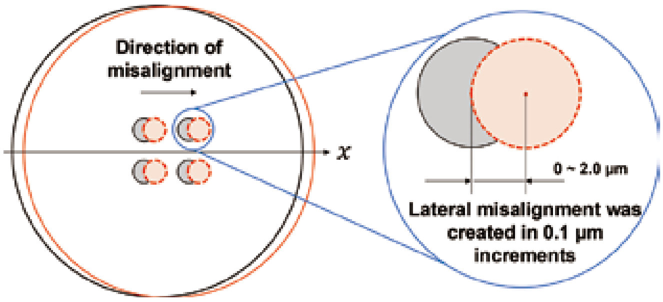
■ Figure 2



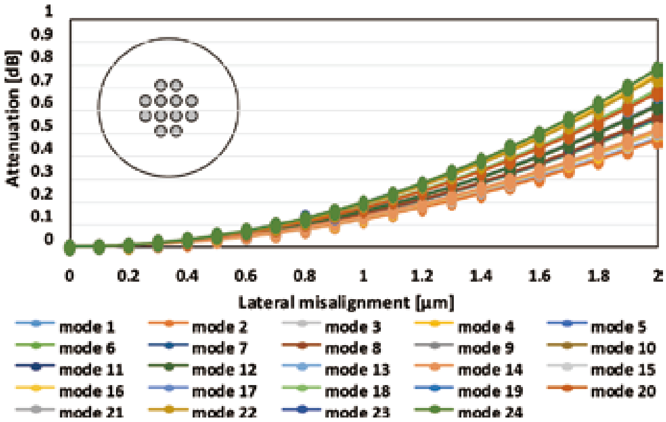
■ Figure 3



■ Figure 4



■ Figure 5



4. Conclusion

We measured attenuation, one of the important characteristics of C-MCF connectors, of the C-12CF optical connectors by random-mated connection test and found that average attenuation was 0.12 dB. The measured attenuation satisfies Grade B in IEC 61755-1, and that result indicates that the performance of the C-12CF optical connectors is sufficient for use in optical communication networks. In addition, compared to previously reported simulation results for attenuation obtained by electromagnetic-field analysis of C-MCF connectors, lateral misalignment of the C-12CF connectors is 0.4 to 1.4 µm. Moreover, changes in the arrangement of the C-MCF measurement setup may cause fluctuations in optical power and mode switching, so a method for accurately measuring attenuation must be further investigated.

Acknowledgements

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PLC Mode-control Device for Mode-division-multiplexing Transmission

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1. Mode-division-multiplexing transmission

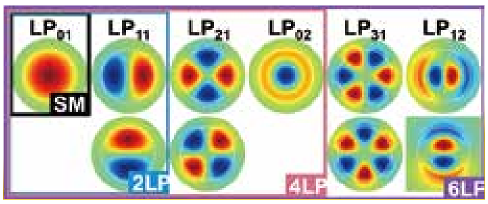
One of the elemental technologies in space-division multiplexing (SDM) optical transmission is mode-division multiplexing (MDM), which multiplexes optical signals with multiple stationary states (namely, modes). Optical fibers with circularly symmetric cores have linear polarization (LP) modes as shown in Figure 1. An optical fiber designed to support a limited number of propagation modes is known as a few-mode fiber (FMF). (The subscripts of LP_{ml} modes represent the azimuthal (m) and radial (l) orders, respectively. For $m > 0$, two modes with different phases degenerate and are distinguished as LP_{11a} and LP_{11b} modes.) FMF achieves higher spatial multiplicity compared to multi-core fiber (MCF), where multiple cores propagating through a single mode (SM) are arranged to achieve spatial multiplicity. FMF, however, exhibits significant differences in transmission characteristics between modes, which can degrade signal recovery accuracy in MIMO signal processing-based transmission systems. This becomes a limiting factor for maximizing transmission distance, making it challenging to extend the number of modes for long-distance transmission. Therefore, in long-distance transmission systems, as shown in Figure 2, it is effective to not only perform optical amplification, but also to implement mode switching and reduce mode loss differences in the repeaters, thereby homogenizing the transmission characteristic differences between modes. This paper introduces a device using a silica planar lightwave circuit (PLC) that performs such mode control.

2. PLC mode multiplexer/demultiplexer

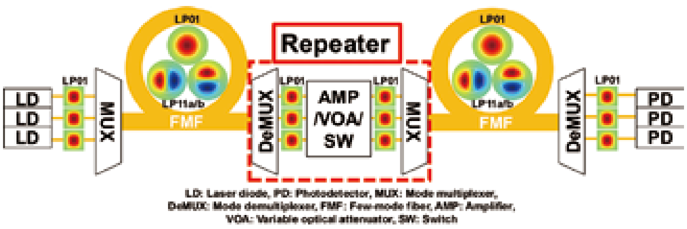
A mode multiplexer (MUX) is required to excite each mode of the FMF with light waves from the semiconductor laser. Due to the reciprocity of light, a mode MUX can also function as a mode demultiplexer (DeMUX) when light is injected in the inverse direction, except in special cases. The PLC mode MUX/DeMUX is highly integrated and enables flexible mode control as described below.

Figure 3(a) shows a cross-sectional view of a quartz-based PLC optical waveguide. The core and its surroundings are made of glass like in optical fibers, and light waves travel by total reflection within the high-refractive-index core. Made of the same material as optical fibers, it enables low-loss interconnection. By forming a Y-shaped core (hereinafter referred to as a Y-junction waveguide) as shown in Figure 3(b), it can function as an optical splitter. (Though not strictly accurate, the explanation here is in accordance with the terminology used for fiber modes). Additionally, not only the LP_{01} mode, as shown in Figure 3(b), but also the higher-order LP_{11a} mode, as shown in Figure 3(c), split evenly. The output phases of these modes correspond to the symmetry of the incident modes. Due to the linearity and reciprocity of light, both the superposition state and the

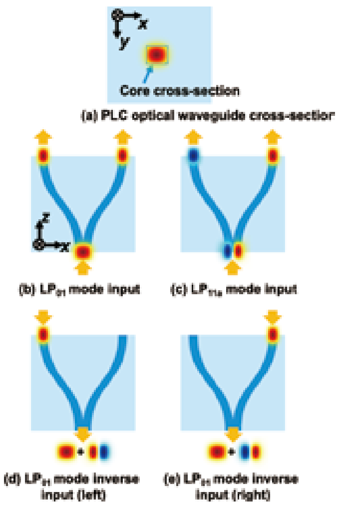
■ Figure 1: Field distribution of LP modes propagating through fiber



■ Figure 2: Example configuration of a long-distance transmission system using FMF



■ Figure 3: Light propagation in a PLC Y-junction waveguide



backward propagation state as shown in Figure 3(b) and Figure 3(c) are valid. In other words, as shown in Figures 3(d) and (e), it means that the LP_{01}/LP_{11a} modes are excited in the lower trunk waveguide when the LP_{01} mode is injected on one side of the upper branch waveguide. Thus, the Y-junction waveguide functions as a type of mode MUX/DeMUX.

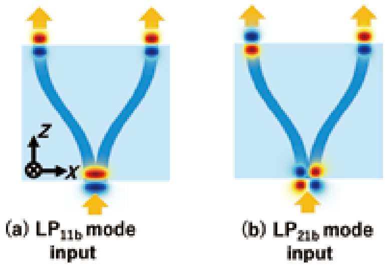
Further, even though equal splitting can be performed with higher-order modes, due to the nature of PLC (as long as processing is done in a single layer), branching can only occur in the x-direction, leaving the order in the y-direction unchanged. Specifically, as shown in Figure 4, the LP_{11b}/LP_{21b} modes are converted to the LP_{11b} mode on the branch waveguide side. However, for mode MUX/DeMUX operations, it is necessary to output the LP_{01} mode at the end. Therefore, a mode rotator (LP_{11a}/LP_{11b} mode switcher) using an L-type waveguide as shown in Figure 5 is useful. By placing this before and after the Y-junction waveguide, the order in the y-direction can be reduced. Consequently, in principle, even when modes of any order are injected, combining the Y-junction waveguide with the mode rotator allows for the output of the LP_{01} mode. Figures 6(a) and (b) show examples of configuration for higher-order modes, and as shown in Figure 6(a), even when the LP_{11b} mode is injected, it is converted to the LP_{01} mode. When injected from the opposite side, it is converted to a superposition of the LP_{01}, LP_{11a}, LP_{11b}, and LP_{21b} modes.

3. PLC-mode-control device

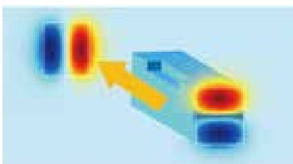
The 4-mode MUX/DeMUX shown in Figure 6 is an example of a specific device that can be used as a mode MUX/DeMUX in the repeater shown in Figure 2. However, simply amplifying each of the LP_{01} modes demultiplexed by the mode MUX cannot compensate for the mode delay differences and loss differences that occur in the FMF before and after the repeater. Therefore, what has been recently considered is an optical matrix multiplier (OMM) circuit for matrix multiplication operations on optical mode amplitudes. Figure 7 shows the basic configuration of OMM, which can obtain the output of four input amplitudes multiplied by an arbitrary unitary matrix U. Although omitted in the figure, a phase-control device and a splitting-ratio-control device are included in addition to the Y-junction waveguide, and arbitrary unitary conversion can be performed by controlling these devices. As shown in Figure 8, by inserting an optical amplifier and attenuator between two OMMs (Figure 7), the transfer matrix can be represented by $T = USV^{\dagger}$. This is a matrix representation of the singular value decomposition, which means that optical amplitude conversion by arbitrary matrices is possible. Appropriately setting the transfer matrix makes it possible to arbitrarily control mode switching and gain/loss differences, thereby enabling compensation for mode transmission characteristic differences corresponding to the FMF links in the preceding and subsequent stages. However, in this configuration, only a simple linear conversion is performed, and the delay cannot be compensated by the repeater alone. Averaging the difference in mode delay by switching modes in multiple repeaters is effective in compensating for the difference in delay between modes.

Thus far, six-mode MUXs have already been reported, and we will focus on studying mode MUX/DeMUX and mode-control devices for further expansion of the number of modes going forward.

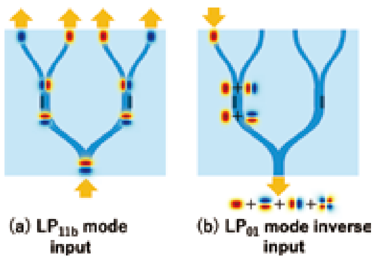
■ Figure 4: Higher-order-mode light propagation in a PLC Y-junction waveguide



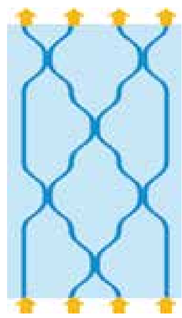
■ Figure 5: Mode rotator using an L-type waveguide



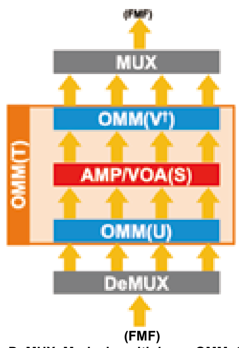
■ Figure 6: Example configuration of 4-mode MUX/DeMUX



■ Figure 7: Example configuration of a 4x4 optical unitary converter



■ Figure 8: Example configuration of an arbitrary mode-control device in a repeater



MUX: Mode multiplexer, DeMUX: Mode demultiplexer, OMM: Optical matrix multiplier, AMP: Amplifier, VOA: Variable optical attenuator
U, V†: Unitary matrix, S: Real diagonal matrix,
T: Arbitrarily configurable conversion matrix

= A Serial Introduction Part 1 =
Winners of ITU-AJ Encouragement Awards 2024

In May every year, The ITU Association of Japan (ITU-AJ) proudly presents ITU-AJ Encouragement Awards to people who have made outstanding contributions in the field of international standardization and have helped in the ongoing development of ICT.
These Awards are also an embodiment of our sincere desire to encourage further contributions from these individuals in the future.
If you happen to run into these winners at another meeting in the future, please say hello to them.
But first, as part of the introductory series of Award Winners, allow us to introduce some of those remarkable winners.

Mikiya Agata

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Fields of activity: WRC-23 (Agenda Item 1.17), ITU-R SG5 WP5D (IMT-2030 framework)

Resolution of Issues in WRC-23 and Development of IMT-2030 Framework Recommendations

I would like to express sincere appreciation upon receiving this prestigious ITU Association of Japan Encouragement Award.

I participated in WRC-23, which is in charge of agenda item 1.17 (additional allocation for inter-satellite services) focusing on protecting terrestrial services from satellite interference.

At the meeting, there were different proposals for the protection criteria from satellite and terrestrial parties, so we had many discussions to unify them. As a result, we reached consensus on protection criteria appropriate for terrestrial service protection.

In addition, developing the IMT-2030 Framework Recommendation, to achieve approval of the recommendation by the deadline, we promoted collaboration with related countries, coordinating their respective needs to finalize the draft Recommendation.

From these experiences, we have learned that when conflict arises, it can be resolved by 1) clearly communicating the objectives to both sides, 2) providing a logical and accurate evaluation, and 3) consolidating opinions fairly.

I would like to contribute to WRC-27 by making the best use of my experience to reach a good conclusion.

Ryusuke Utsunomiya

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Fields of activity: Interference coordination, ITU-R standardization

Successful Establishment of WRC Agenda Item for Direct Connectivity between Satellite and Mobile Phones

I would like to offer sincere appreciation for this ITU-AJ Encouragement Award. I would also like to thank everyone at the ITU-AJ, and all who participated in activities toward establishing the agenda item for satellite direct communications at the WRC.

Satellite direct communications is a technology for communications directly between satellites and existing mobile telephone equipment. Implementing it will enable phone calls and other smartphone communications in areas where it was previously difficult, using existing mobile phone lines. To realize such a service, both adjustments to domestic systems and international standardization will be imperative. Since 2022, I have participated in ITU-R meetings to promote discussion at the WRC.

I submitted the first proposal for discussion of satellite direct communications at APG23-6, hoping to submit an APT common proposal together with other APT members who share a common interest, but we did not reach agreement. We negotiated hard with each country, making compromise after compromise and finally brought it to the plenary meeting, but in the end, some administrations opposed. I keenly felt that international negotiation is not easy or straightforward.

At the 3rd ITU Inter-regional Workshop and the following WRC-23, I collaborated with other businesses and held bilateral meetings and negotiations with each country as the APT coordinator. Also, based on guidance from the Ministry of Internal Affairs and Communications, we created leaflets and other materials to promote the concept of satellite direct communications and details of the Japanese proposal and lobbied by holding an event at WRC-23. We received much support and cooperation until finally, with most of the administrations giving their support and agreement to the shared understanding, it was accepted as an agenda item for WRC-27.

I will continue working to achieve the result that Japan hopes for, a resolution at WRC-27.

Kyohei Unno

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Fields of activity: ITU-T Q6/16 (VCEG), ISO/IEC JTC1/SC29/WG5 (JVET), WG7 (MPEG-3DGH)

Contributions to the International Standardization of Video Coding and Point Cloud Coding

I am deeply honored to receive the ITU Association Encouragement Award. I would like to express my sincere gratitude to the ITU Association of Japan and everyone who has supported me thus far.

Since joining KDDI Research in 2018, I have been actively involved in the international standardization of video coding technologies within ITU-T Q6/16 (VCEG) and ISO/IEC JTC1/SC29/WG5 (JVET). I contributed to establishing the latest international video coding standard, H.266, by proposing several technologies to improve coding efficiency with over 60 contribution documents. I also contributed verification data for H.266.1, a standard for verifying the interoperability of H.266, contributing to recommendation. H.266 is being considered for adoption in the next generation of terrestrial digital broadcasting in Japan. I sincerely hope that H.266 will be widely used globally in the future.

Since 2020, I have also participated in the international standardization of point cloud coding technologies, V-PCC and G-PCC, within ISO/IEC JTC1/SC29/WG7 (MPEG-3DGH). Particularly in G-PCC, I made numerous contribution proposals and contributed to the publication of G-PCC 1st edition in 2023. For study on the G-PCC 2nd edition, which began in 2021, I mainly proposed techniques related to Trisoup, a method for encoding geometry (coordinate) information. Currently, I lead the development of this technology as the exploration experiment coordinator. Recognizing these efforts, I am now one of the editors for G-PCC 2nd edition. Although the widespread adoption of G-PCC is still in its early stages, I hope that it will also be widely beneficial to society.

Once again, I am deeply grateful for this prestigious recognition and will continue to strive for excellence in my contributions to international standardization efforts.

Junichi Kawasaki

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Fields of activity: ETSI ISG ZSM, ITU-T SG13

Standardization Activities toward Network Automation Using AI/ML

It is a great honor for me to receive the ITU-AJ Encouragement Award, and at this time, I would like to extend my deep appreciation to everyone at the ITU-AJ and to those who supported me in standardization activities up to now. In 2018, when I began to participate in standardization meetings, it was a time of much progress in network virtualization. Expectations were growing toward network automation that could guarantee communications quality without human intervention in a network that was becoming increasingly complex. There was much activity in this area at related standardization organizations (ITU-T, ETSI, TM Forum, etc.) and open source communities (ONAP, etc.) During this time, I submitted proposals for achieving network automation and drafted specifications for closed-loop automation mainly at the ETSI ISG ZSM group. Additionally, I participated in research and development activities toward the use of AI/ML in network automation as a Japanese national project. I made proposals based on this project at ITU-T SG13 in collaboration with project partners and formed them into a ITU-T Recommendation as a framework for network automation using AI/ML. The results of this research and development were also applied to problems related to network failure detection posed at a competition held by ITU with the aim of expanding the application of AI/ML to network operations. We were therefore able to connect our R&D achievements to the development and spread of this technical field. At present, standardization activities toward 6G are beginning, and I believe that operations technology using AI/ML will become even more important in the 6G era from the viewpoint of resilience. I will continue to contribute to the realization of a reliable network infrastructure through the development of network operations technology together with partners both in Japan and abroad while leveraging the experiences I have had through my activities to date.

通巻百四十四号

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