EXAT Study Group: 15 Years of Progress

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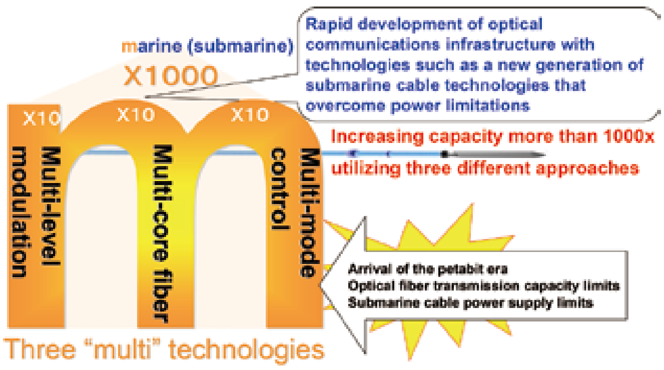
1. Introduction

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.

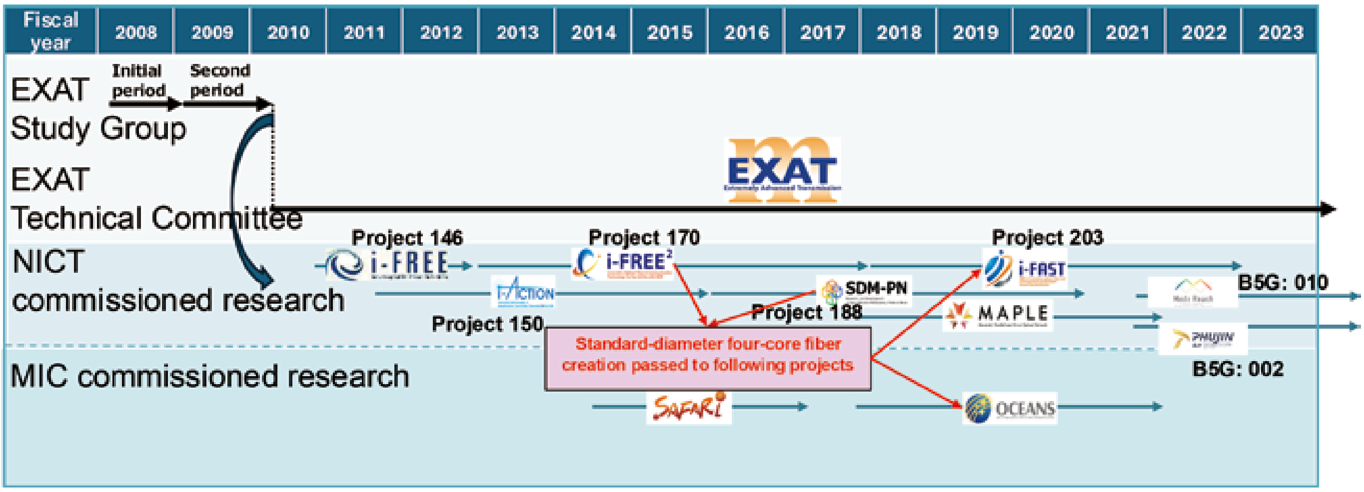
4. NICT/MIC EXAT-related national projects

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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