Front-line Researchers

Turning an Innovative Idea into Common Sense and Making It Useful to Society

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Abstract

With the increase in video-data distribution, the development of cloud technology, and spread of new information and communication services, such as 5th-generation mobile communications and remote work, information and communication traffic has been increasing and will continue to increase. Implementation of the All-Photonics Network of IOWN (the Innovative Optical and Wireless Network) to meet the demand for diverse services and exponential growth of data traffic will require a huge increase in transmission capacity as well as drastic reductions in power consumption and latency. NTT Fellow Yutaka Miyamoto at NTT Network Innovation Laboratories is pioneering new optical network technology to overcome the capacity crunch. We interviewed him about the progress of his research and what is the best part of being a researcher.

Keywords: scalable optical transport network, optical-amplification repeater, space-division multiplexing

Developing fundamental technologies for high-capacity scalable optical transport networks

—Could you give us an overview of the research you are currently conducting?

To implement a scalable optical transport network with petabit per second (Pbit/s)-class link capacity that can accommodate communication traffic that will increase due to the expansion of cloud services and spread of smartphones, I'm conducting research on four fundamental technologies: (i) large-scale digital-signal-processing technology for optical communications; (ii) photonics-electronics convergence integrated circuit (IC) technology; (iii) ultra-low-noise optical-amplification technology for signal-to-noise-ratio improvement; and (iv) space-division multiplexing (SDM) optical-transmission-system technology.

NTT has been a world leader in research and development (R&D) of optical communication technology. Since the practical application of time-division multiplexing systems in 1981, NTT has continued to drive three paradigm shifts concerning optical transmission systems: optical-amplification repeater systems, wavelength-division multiplexing (WDM) systems, and digital-coherent systems. As a result of these shifts, transmission capacity has increased

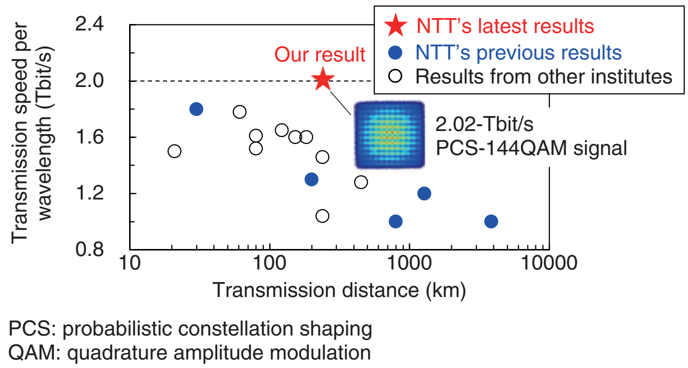

Fig. 1. Extending transmission distance of multi-terabit-class optical signals by increasing modulation rate.

approximately one million times in the past 40 years.

Data traffic has continued to increase at a rate of about 1.4 times per year, and as 5th-generation mobile communications (5G) and the Internet of Things services begin to be rolled out widely and 6G services are also in sight, communication traffic is expected to continue to grow exponentially. In fact, it is predicted that long-distance transmission with Pbit/s-class capacity will be necessary in the 2030s. To meet such future communication demands, the Innovative Optical and Wireless Network (IOWN) aims to economically provide higher capacity through the All-Photonics Network (APN).

However, recent research has shown that the physical limit on transmission capacity (namely, the capacity crunch) of long-distance transmission using optical fibers currently in use becomes apparent around 100 terabits per second (Tbit/s). To overcome the technical challenges posed by the capacity crunch and implement a Pbit/s-class optical communication infrastructure that can accommodate more than 100 times the current data traffic in a low-power consumption and economical manner, my research colleagues and I are conducting R&D on scalable optical transport technologies. We are driving the fourth paradigm shift through technological innovation that combines the advancement of optical transmission technology that we have been developing with new optical transmission medium (optical fiber) technology.

—Since our last interview two years ago, you have continuously tackled the technical issues concerning the capacity crunch.

In the previous interview, I talked about the results of our R&D at that time, including (i) SDM optical communication technology that can increase transmission capacity per link to more than 1 Pbit/s, which was more than 125 times the capacity of practical WDM systems using current optical fiber (100 Gbit/s/wavelength), and (ii) the demonstration of long-distance WDM transmission exceeding 1 Tbit/s per wavelength, both of which were the world's first at the time.

These achievements were the result of timely collaboration with the transmission medium and device research departments within NTT laboratories as well as external research institutes. We have continued to develop these technologies through close collaboration among our research departments, especially those among young researchers, and were able to produce world-first and world-leading research results in FY 2022.

For example, in 2022, we experimentally demonstrated the world's first optical amplified transmission using digital-coherent optical signals exceeding 2.02 Tbit/s per wavelength over 240 km (**Fig. 1**).

To expand transmission capacity per wavelength by overcoming the speed limit of silicon complementary metal oxide semiconductor circuits, we had to both broaden bandwidth and increase output power of the driver amplifier for driving the optical modulator as well as achieve extremely accurate compensation for differences in tributary-signal-path lengths and variations in tributary-signal-path loss in the optical transmitter and receiver circuits. We addressed this issue by integrating an ultra-broadband baseband-amplifier IC module and digital-signal-processing technology that enables ultra-high-precision compensation of loss variation and distortion in the optical transmitter and receiver circuits, both of which were developed by NTT, and achieved optical amplified transmission

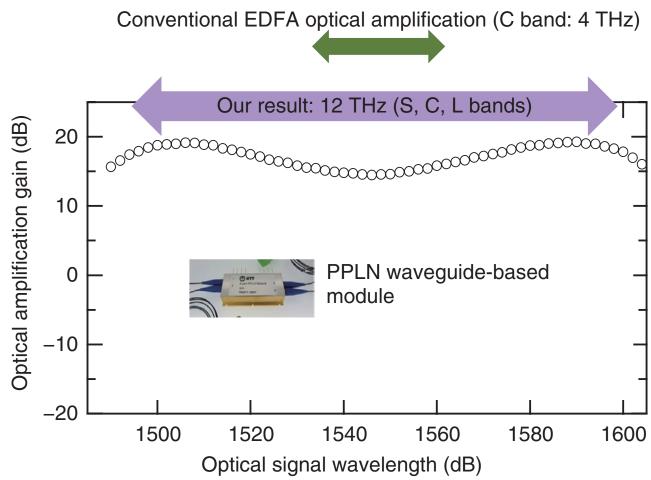

Fig. 2. Broadening the amplification bandwidth and expanding wavelength resources by applying optical-parametric amplification repeater system using PPLN waveguide modules.

over a distance of 240 km at 2.02 Tbit/s. This result indicates the potential for further scalability of digital-coherent optical-transmission technology that can achieve both high capacity and long-distance transmission. A paper reporting this achievement was accepted as a postdeadline paper—a paper presented at the most-challenging session—at the European Conference on Optical Communication (ECOC 2022).

Conducting experiments in historic facilities at NTT Yokosuka R&D Center

—You are developing core technology for the IOWN APN, right?

We also made significant progress in terms of broadband optical-amplification repeater technology using NTT's proprietary periodically poled lithium-niobate (PPLN) waveguide modules.

In close cooperation with the device research department, we proposed an optical-amplification repeater system that combines an optical parametric inline amplifier that handles polarization-division-multiplexed digital-coherent optical modulation and demodulation signals, which are currently the mainstream. We conducted the world's first ultra-wideband WDM optical amplified transmission experiment over 240 km by applying an optical parametric amplifier to multiplex optical signals at 1 Tbit/s per wavelength within the amplification bandwidth of 12 THz (**Fig. 2**).

While the WDM signal bandwidth of the widely used optical amplifier (erbium-doped fiber amplifier (EDFA) in the C band) is approximately 4 THz, our newly developed optical-parametric amplifier can amplify a bandwidth of 12 THz or greater, which is approximately three times that of an EDFA, and can cover the wavelength regions (S, C, and L bands) in which optical fiber has low loss. It is thus possible to expand wavelength resources by broadening bandwidth. This broadband optical-amplification repeater technology, with its wide bandwidth and low distortion, is expected to provide further high-capacity optical amplification enabling implementation of the APN, which dynamically uses abundant wavelength resources in accordance with the IOWN concept proposed by NTT. This accomplishment was also accepted as postdeadline papers at the Optical Fiber Communication Conference (OFC) in 2021 and 2022.

—You are also working closely with the transmission medium research department on SDM optical communication technology.

In addition to broadening the bandwidth of conventional single-mode optical fibers (SMFs), we are promoting R&D on optical fibers for SDM optical communication technology with the aim of fundamentally overcoming the capacity crunch. Working closely with the transmission medium research department, we are developing prototypes of various types of SDM optical fibers, including multicore optical fibers (MCF) having multiple cores (which are pathways for light) in a single fiber and multimode optical fibers having multiple propagation states (spatial modes) in a single core, and are assessing the feasibility of these optical fibers as new transmission media for future optical communications. To maximize the performance of the above-mentioned new transmission media, we are also studying high-capacity SDM optical communication systems.

Since SDM optical fiber with a standard cladding diameter of 125 µm (which is the same diameter as that of current SMF) is suited for mass production of optical-fiber cables, we are investigating SDM optical communication technology that can increase the capacity of such fiber more than ten times that of current SMF while maintaining a standard cladding diameter. We have been focusing our research on mode-multiplexed transmission technology that uses and controls multiple spatial modes to overcome the limitation on transmission distance imposed by interference (crosstalk) between different spatially multiplexed optical signals, which is an issue regarding SDM optical communication systems. Mode-multiplexed transmission technology consists of the following three technologies: (i) mode-multiplexing optical-fiber cabling technology, which can control spatial modes; (ii) mode-multiplexed multiple-input multiple-output (MIMO) digital-signal-processing configuration technology, which can multiplex and demultiplex multiple different optical signals at the same wavelength in accordance with dynamic optical characteristics attributed to the cable-installation properties; and (iii) fundamental transport technology that unifies the spatial-mode-multiplexing optical-amplification repeater technology with (i) and (ii).

Regarding mode-multiplexed MIMO digital-signal-processing configuration technology, NTT successfully demonstrated in a proof-of-principle experiment long-distance transmission over 6000 km of mode-multiplexed optical communications using six independent spatial modes. For this experiment, we developed a MIMO signal-processing system and optical-amplification repeater system that have strong compensation characteristics against transmission loss and propagation-delay differences that occur between different spatial modes. In March 2023, we also reported in our highly scored OFC 2023 paper the demonstration of long-distance mode-multiplexed optical-amplified transmission with ten spatial modes.

Research on the above three technologies has partly been supported by National Institute of Information and Communications Technology under the "R&D of basic technologies of spatial mode control type optical transmission for the Beyond 5G era" program (started in 2021). We are collaborating with four domestic research institutes and NTT Access Network Service Systems Laboratories to establish an SDM optical transmission system that will enable us to build a high-capacity, long-distance backbone optical network in the Beyond 5G era. Specifically, we are investigating the following technologies: (i) design, installation, and connection technologies for coupling-type MCF cable that has a standard cladding diameter and can control spatial modes; (ii) optical-amplification repeater technology that is compatible with MCF cabling technologies (i); and (iii) a new low-complexity MIMO signal-processing technology that can follow dynamic changes in the transmission link. By investigating these three technologies, we aim to establish a basic technology for spatial-mode-control optical transmission that enables long-distance transmission of spatially multiplexed signals of ten or more.

Over the last few years, our research has advanced to the stage of installing various types of SDM optical-fiber cables in underground facilities at the NTT Yokosuka R&D Center and testing their transmission characteristics under conditions similar to those in the field. The NTT Yokosuka R&D Center, which celebrated its 50th anniversary in 2022, has an underground facility (conduit) built in the 1970s to verify wired communication system technology. Optical-fiber cables developed at the dawn of optical-fiber-communication systems in the mid-1970s were laid, and tests on the characteristics of those cables in terms of practical use were conducted. We are taking on the challenge of conducting new demonstration experiments at this historical site, where our predecessors have been testing technology and putting it to practical use for more than 40 years.

Collaborating with others like the tale of the "three arrows" to accumulate achievements

—Can you tell us what is key in your research activities?

Optical communication systems cannot be put into practical use by using only a single technology. The process of achieving target performance in a timely manner by combining several of our technologies with those of various companies and institutes as necessary is important. Given the rapid pace of change in the world today, it is essential to promote collaboration within other research institutes and other laboratories within NTT in a timely manner to take the lead in standardization activities and keep ahead of global competition. We need to combine multiple advanced technologies as in the tale of the "three arrows" (which conveys that one arrow can be easily broken, but three bundled arrows cannot) to achieve results and build a track record.

I believe that one of my roles as an NTT Fellow is to create opportunities for young researchers to test their ideas and collaborate effectively with other leading researchers. To fulfil that role, it is of course important to have advanced technologies of our own, but it is also important to share the goal to be reached with other researchers and research institutes that have advanced technologies and build a relationship of trust with them. I try to find partners who share our goals through joint experiments and at academic conferences and collaborate with them in a timely manner. I believe that if our ultimate goal is in line with our collaborative partners, we can get back to the basics and move forward without wavering, even if difficulties arise. If we are working with overseas research institutes, we may face differences in cultures, business practices, and mentalities, so we may need to take subtle tactics; even so, when taking up a challenge concerning a new technology, I want to keep a positive mindset and say, "It looks interesting and challenging, so let's give it a try."

As I mentioned in the previous interview, I believe it is important to be prepared on a daily basis so as not to miss any critical "This is it!" moments. For this reason, it is also important to identify the areas in which we produce technology that surpasses others and has value. We also need to pay attention to what value we can provide to our collaborative partners. Since this perspective can be lost when focusing on cutting-edge technologies only, we are working on both R&D and practical applications in conjunction with our colleagues in the practical application department.

—What is important to be a good researcher?

I said before that an important perspective for system researchers is to "turn an innovative idea into common sense and make it useful to society." I want to tell young researchers that everything starts from an innovative idea. For example, when we first presented a research result at a conference, the reaction was not so great; however, at the next conference, many people presented something similar, creating a technological trend.

I urge all researchers to pursue what you find interesting without fear of failure. However, it may be difficult to determine how long you need to pursue it. There were many cases in which a technology that had remained obscure became widespread when combined with another technology 20 years later. It is also important to investigate things over a long time span without being too concerned about the results in front of you and obtain rights to your ideas in preparation for the day that they are put to practical use.

As a final point, in the spring of 2021, on behalf of all my colleagues, I was honored with receiving the Medal with Purple Ribbon for the development of a high-capacity optical transmission scheme using coherent-multicarrier multilevel modulation. The subject of this award is related to the R&D on long-haul high-capacity optical-fiber communication systems, with which I was involved from 1995 to 2010. In 2007, the technology that won this award was put to practical use for the first time in NTT Group's 1.6-Tbit/s WDM optical communication system with a channel capacity of 40 Gbit/s per wavelength. Our major contributions include the practical application and international standardization of (i) digital-signal multiplexing/framing—called the optical transport network (OTN)—equipped with strong error-correcting codes to flexibly accommodate data traffic in WDM optical networks and (ii) multilevel differential phase shift keying for replacing the intensity-modulation direct-detection technology. The above technologies we have developed facilitated the spread of the Internet and global broadband services via optical access networks and smartphones (4G) and continue to support the communication infrastructure that is deeply involved in the transformation of people's businesses and lifestyles. It is most gratifying to me that the contribution of the research field that we have been pursuing, including those of our predecessors who have guided us and the many people that we have worked hard with to advance R&D and practical applications, have been recognized. Being able to engage in R&D that will produce results that will be used around the world and contribute to society as a whole is the best part of being a researcher.

■ Interviewee profile

Yutaka Miyamoto received a B.E. and M.E. in electrical engineering from Waseda University, Tokyo, in 1986 and 1988 and Dr.Eng. in electrical engineering from the University of Tokyo in 2016. He joined NTT Transmission Systems Laboratories in 1988, where he engaged in R&D on high-speed optical communications systems including the 10-Gbit/s first terrestrial optical transmission system (FA-10G) using EDFA inline repeaters. He was with NTT Electronics Technology Corporation between 1995 and 1997, where he engaged in the planning and product development of a high-speed optical module at the data rate of 10 Gbit/s and beyond. Since 1997, he has been with NTT Network Innovation Labs, where he has researched and developed optical transport technologies based on 40/100/400-Gbit/s channel and beyond. He is currently investigating and promoting a future scalable optical transport network with Pbit/s-class capacity. He is a member of the Institute of Electrical and Electronics Engineers (IEEE) and a fellow of the Institute of Electronics, Information and Communication Engineers (IEICE).