Research and Development of Scalable Optical Transport Technologies

Yutaka Miyamoto, Kei Watanabe, and Kazuhide Nakajima

Abstract

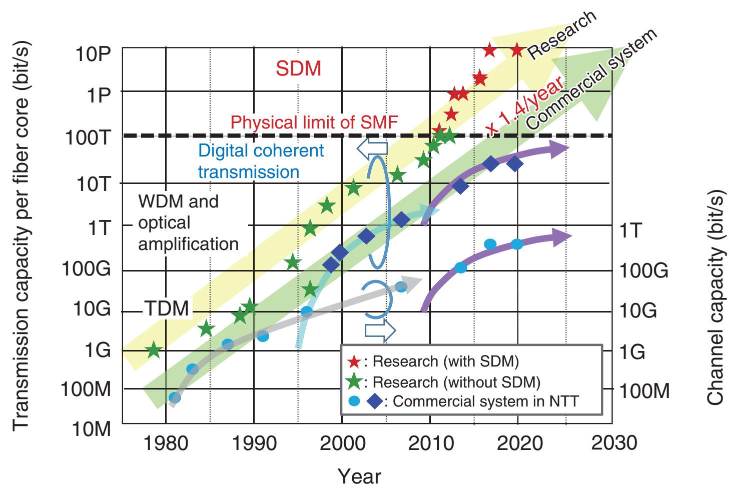
This article discusses the current state and prospects of scalable optical transport technologies that can dramatically expand the optical amplification and electrical signal processing bandwidths for achieving a Pbit/s-class long-range optical network toward IOWN (the Innovative Optical and Wireless Network) All-Photonics Network. We explain the optical parametric amplification repeater technology, which has the potential to achieve longer transmission distances while expanding the amplification bandwidth of conventional optical amplification repeaters by more than 2.5 times. We also look into the space division multiplexing optical communication technology that uses multiple-input and multiple-output signal processing and has the potential to increase transmission capacity by more than 10 times at the same cladding diameter as conventional optical fibers.

Keywords: ultra-large-capacity optical communications, optical parametric amplification repeater, mode-multiplexing optical communications

1. Introduction

The fifth-generation mobile communications (5G) system was introduced commercially in Japan in FY2020. The 5G system is forecast to evolve into an infrastructure for the Internet of things society in which all things, including autonomous driving, connect to highly reliable, low-latency, and large-scale networks. With the acceleration of the evolution of network infrastructure technologies through the development of the Innovative Optical and Wireless Network (IOWN) All-Photonics Network (APN), next-generation Beyond 5G technologies following the 5G system are expected to be widely used as network service technologies in the 2030s. The continued evolution of the network infrastructure is considered essential for flexibly supporting changes in the global industrial structure and in lifestyles brought about by the COVID-19 pandemic.

A high-capacity network infrastructure that supports the evolution of broadband services requires the continued evolution of high-capacity optical transport networks. NTT, as shown in **Fig. 1**, has been pursuing the continued development of high-capacity optical transport systems and networks based on single-mode fiber (SMF) cables, which were introduced in the 1980s. The system capacity per fiber core, along with the continuous technological innovations of various optical communication systems, has evolved at a rate of nearly 1.4 times per annum (1000 times in 20 years), wherein the system capacity is expected to exceed 1 Pbit/s by the 2030s. Digital coherent optical communication technology using digital signal processing has been commercialized as a transmission technology that takes advantage of the coherent nature of lightwave and maximizes the transmission characteristics of SMF. In 2019, an optical transport network with a capacity of 16 Tbit/s per fiber core was commercialized [1]. However, it has become clear that the physical capacity limit (capacity crunch) of SMF, a transmission medium that has supported long-distance optical transport network infrastructure, exists near the 100-Tbit/s capacity, which is approximately 10 times that of the current



SDM: space division multiplexing
TDM: time division multiplexing
WDM: wavelength division multiplexing

Fig. 1. Evolution of ultra-large-capacity optical communication system technologies.

capacity, pointing to the need for innovative technologies to achieve continued growth in system capacity.

This article describes two approaches to overcome the capacity crunch toward the IOWN APN through scalable optical transport technologies. The first is a broadband optical parametric amplification repeater technology that economically increases the SMF capacity by expanding to more than twice the optical signal bandwidth of optical amplification repeaters using conventional SMF. The second is a space division multiplexing (SDM) optical communication technology that creates multiple independent parallel communication channels multiplexed by introducing new degrees of freedom, such as multi-cores and multi-modes, in a single strand of optical fiber to achieve high-capacity communication in the Pbit/s-class capacity beyond the limit of current SMF. The following sections describe the recent progress in the individual technology elements.

2. Broadband optical parametric amplification repeater technology

For the current optical fiber transmission systems, large-capacity transmission has been achieved by multiplexing optical signals of approximately 100 wavelengths into the optical wavelength band of around 4 THz, which is the amplification bandwidth of an erbium-doped optical fiber amplifier (EDFA), and by expanding the transmission capacity per wavelength of an optical signal using digital coherent technology*1. For the APN, which is part of the IOWN initiative proposed by NTT, we are aiming to build a flexible optical network that uses abundant wavelength resources. Along with increasing conventional capacity per wavelength, we are also aiming to expand the available wavelength resources (optical wavelength band). NTT has been pursuing research and development (R&D) focusing on optical parametric amplification*2 using a periodically poled lithium niobate (PPLN)*3 waveguide as a wide-band and low-distortion optical amplification technology

*1 Digital coherent technology: A transmission method that combines massive digital signal processing and coherent detection. Coherent detection enables a high-sensitivity receiver for the amplitude and phase modulated optical signals by introducing interference between the light source placed on the receiving side and received light signal. In addition to increasing spectral efficiency through polarization multiplexing and modulation schemes using amplitude and phase of optical signals, digital coherent technology can achieve higher receiver sensitivity through high-precision distortion compensation of optical signals using digital signal processing in combination with the coherent detection.

*2 Optical parametric amplification: Light at a specific wavelength is amplified through interaction between light of different wavelengths using the nonlinear optical effects generated in the material. High-nonlinear fibers and lithium niobate ($LiNbO_3$) crystal are known as nonlinear media.

*3 PPLN: An artificial spontaneous-polarization crystal in which the directions of positive and negative charges in the crystal are forcibly inverted at a fixed period in a nonlinear medium, e.g., $LiNbO_3$. PPLN enables a nonlinear optical effect that is significantly higher than that of the original $LiNbO_3$ crystal.

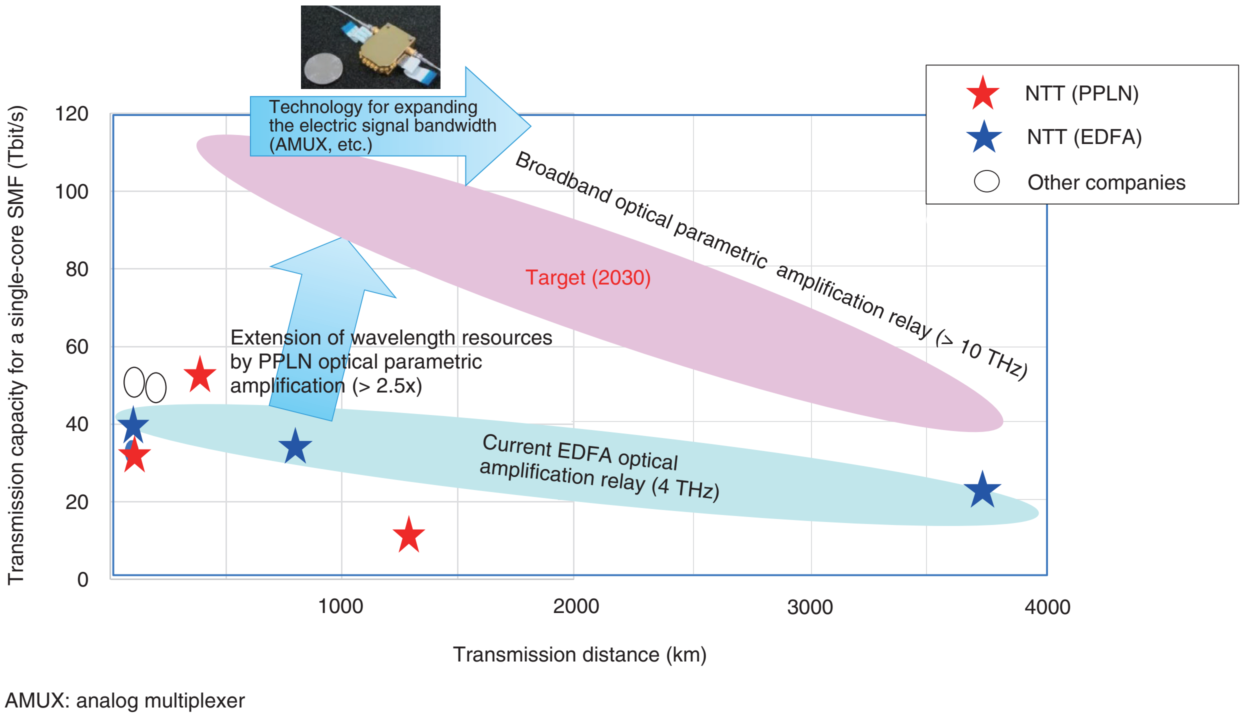


Fig. 2. Expansion of existing SMF transmission characteristics through broadband optical parametric amplification repeater technology and electric signal bandwidth expansion technology. All plots are experimental results with the channel rate ≥ 800 Gbit/s and optical amplification bandwidth > 4 THz.

[2]. Optical parametric amplification with a PPLN waveguide can only amplify a single polarized signal and produce phase conjugated light that is unnecessary for normal optical amplification. These factors, therefore, posed further challenges in widening the amplification bandwidth and in achieving stable response for frequent insertion and removal of optical wavelengths in response to traffic demand in the future APN with the optical amplification of polarization-multiplexed optical signals currently used in digital coherent systems.

Therefore, we proposed an amplifier configuration using multiple modular PPLN waveguides (PPLN modules) to achieve stable amplification of polarization-multiplexed optical signals and the amplification bandwidth of 10.25 THz with a gain of at least 15 dB. Using the ultra-high-speed signal-generation technology [3] with a symbol rate of over 100 Gbaud and using polarized multiplexed digital coherent signals of 800 Gbit/s per wavelength as verification signals, we confirmed low-distortion signal amplification in the gain-saturation region for both single-wavelength and wavelength-multiplexed signal inputs. We also confirmed the high-speed response to input signal switching at 1 wavelength and 41 wavelengths through emulation of the high-frequency variation in the number of wavelengths expected for the utilization of wavelength resources in the APN. We introduced the optical parametric amplifier as a wideband inline repeater and demonstrated that the optical signal bandwidth can be expanded to more than 10.25 THz, more than 2.5 times that of conventional technology, using wavelength-multiplexed signals of 800 Gbit/s per wavelength [4].

Going forward, we will pursue research on long-distance transmission performance at 100 Tbit/s, which is close to the performance limit of current optical fiber communication systems, as shown in **Fig. 2**, by combining broadband optical parametric amplification repeater technology and ultra-high-speed signal-generation technology with high symbol rate.

3. SDM optical communication technology using mode multiplexing

SDM optical communication technologies are expected to overcome the SMF capacity crunch and

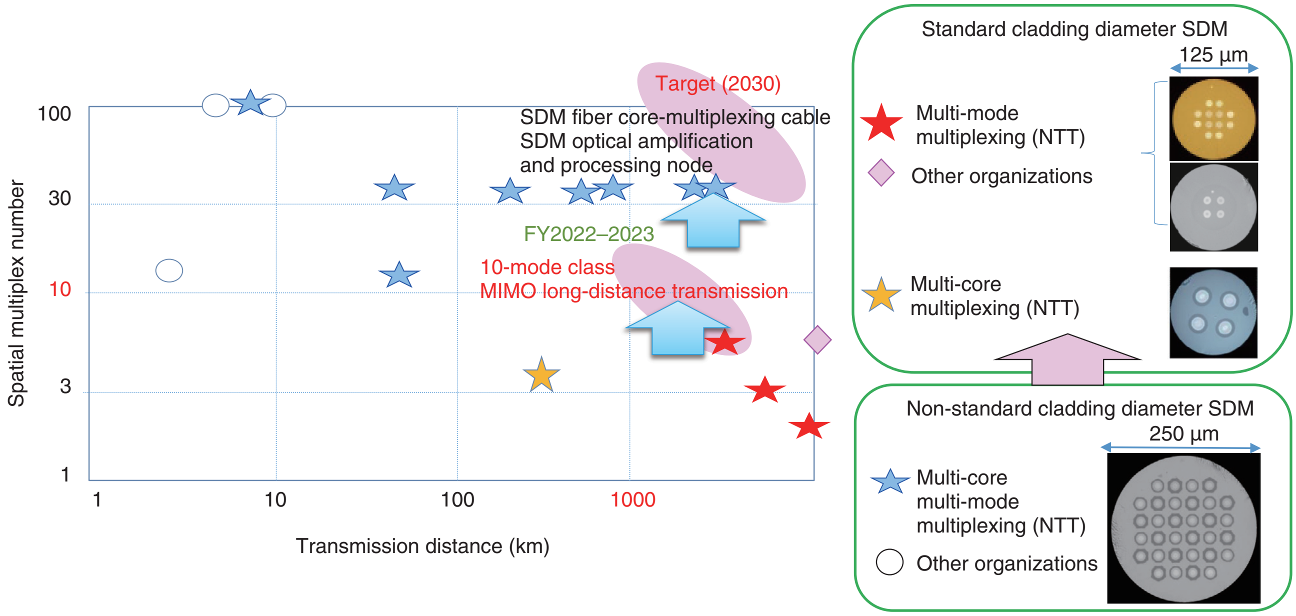


Fig. 3. Overcoming the capacity crunch using mode-multiplexed MIMO signal processing and standard cladding diameter mode-multiplexed fiber mounting technology (spatial multiplexing = 1 is the current SMF transmission system capacity).

achieve a larger capacity. In consideration of the manufacturability of SDM optical fiber cable, which serves as the novel transmission medium, should be equivalent to the standard cladding diameter (125 µm) of the currently widely used SMF. When using multiple cores and propagation modes to transmit signals using SDM optical fiber with the standard cladding diameter, especially in areas with more than four space multiplexes, strong mode couplings between each spatial mode occur, and cross talk and spatial mode dispersion (SMD) lead to significant distortion of the signal waveform. In the current digital coherent optical transmission system using SMF, polarization multiplexing is applied to transmit independent signals using two different polarizations. The dynamic waveform distortion caused by the combination of polarization rotation in the transmission path and the delay difference between the polarized waves (polarization mode dispersion) is adaptively compensated by 2 × 2 multiple-input and multiple-output (MIMO) signal processing*4 implemented in the digital signal processing circuitry in the receiver to achieve high-quality transmission. However, if this is simply expanded and applied to the mode-multiplexed SDM transmission system, the size of the MIMO signal processing circuit increases proportionately to the square of the spatial multiplex number. Furthermore, the number of digital filter taps required for MIMO signal processing must be expanded accordingly since the SMD inherent in multi-mode fiber is 10 times larger than polarization mode dispersion and accumulates proportionally to the square root of the transmission distance in multi-mode fibers with large mode coupling.

To overcome the above technical challenges, we are investigating high-capacity, long-distance optical transport technologies that actively use and control the spatial modes (**Fig. 3**). Specifically, we are aiming to establish: (1) spatial mode-control optical-fiber cabling technology with a standard cladding diameter of 125 µm suitable for fiber-optic cable installation environments and mass production, (2) mode-multiplexing MIMO processing configuration technology that takes into account the dynamic optical characteristics attributed to the cable installation properties, and (3) the fundamental technology that organically

*4 MIMO signal processing: A technology that transmits and receives one or more signals on a transmission path with multiple signal propagation paths (propagation modes and cores) using the same carrier frequency (wavelength). It is a widely used technology in radio communications. In optical communications, MIMO with two inputs and two outputs (2 × 2) using two orthogonal polarization modes within SMF has been commercialized using digital coherent technology as a polarization multiplexing technology.

links the spatial mode-multiplexing optical amplification repeater technology integrating (1) and (2). As an example of the results of recent studies on mode-multiplexing MIMO processing configuration technology [5], in the mode-multiplexing optical communications using six independent spatial modes, we have successfully demonstrated long-distance transmission over 6000 km by proposing an optical amplification repeater system and MIMO signal processing system that have strong compensation characteristics against transmission-loss and propagation-delay differences between different spatial modes. We have also successfully demonstrated the effectiveness of a novel implementation technology for controlling optical characteristics in mode-multiplexing transmission fiber in current terrestrial optical fiber cable structures [6]. To establish these fundamental technologies, we are accelerating R&D in cooperation with external partners, which is partially supported by the National Institute of Information and Communications Technology [7].

4. Summary

In this article, we described the current state and future prospects for broadband optical parametric amplification repeater technology and mode-multiplexed SDM optical communication technology that are being studied as scalable optical transport technologies to overcome the capacity crunch toward the IOWN APN.

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He 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 the 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).

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