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Creating Happiness with ICT by Making the World *Smart* and Technology *Natural*

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Overview

The NTT laboratories heretofore have focused on research supporting NTT's own services and systems. However, their strategy has been shifted to the promotion of the B2B2X (business-to-business-to-X) model and now emphasizes *value creation* with partner companies. What is the mindset at the NTT laboratories to advance research and development (R&D) with the aim of creating innovation for people to live their lives more affluently and in a more *natural* manner? Katsuhiko Kawazoe, Senior Vice President and the head of Research and Development Planning, NTT, was asked about his attitude toward R&D that will transform the world.

Keywords: smart world, natural technology, happiness

What kinds of research and development (R&D) and technology make people happy in the true sense?

—It has been half a year since you took up your current position. What do you think so far?

My prior position as the head of a laboratory group was somewhat an extension of my specialties. However, the current position as the head of Research and Development Planning involves managing all the NTT laboratories while also supervising R&D across the entire NTT Group. In other words, I now determine what kind of new world our R&D in different fields should create, and lead the labs to generate new value inside and outside the NTT Group and society through the daily accumulation of research in the labs. As you probably know, we are promoting the business-to-business-to-X (B2B2X) model and have expanded our business activities accordingly. Promoting the B2B2X model is one of the pillars of our medium-term management strategy "Your Value Partner 2025," which encourages us to support the second B in creating new value and to conduct R&D that contributes to that value creation. Our lab members have already been pursuing various efforts in line with this strategy. Moreover, I believe it is vital to further accelerate our R&D by collaborating with more partners, and I'd like to promote this belief under the catchphrase "Making the world smart and technology natural."

As for the meaning of *natural* in that catchphrase, for example, a smartphone is really a convenient tool. However, when we contact someone via smartphone, we first consider what application the other party is using on their smartphone. Then, we consider whether the line is faster by using 4G (fourth-generation wireless) or Wi-Fi and how to send images according to the usage environment, and we change the phone settings accordingly.

This procedure is no problem for smartphone users who do not think it is a burden, but some users do consider it a burden. For the latter users, although most of the current smartphones will automatically connect to a faster network, tasks such as selecting the application and pre-setting are still a considerable burden. We want to reach out to those users—that is, pause just for a while as various functions evolve and enable anyone to use services smoothly. The word *natural* has come up to describe that aspiration. Making technology natural may mean thinking about what function really makes people happy.

Show new possibilities and create the next developments while facing the times

—The catchphrase "Making the world smart and technology natural" reflects your true feelings. What kind of research will make the world smart?

Some studies are aimed at realizing a smart world, however, that is not what this is all about. I think that it is also necessary to bring *smart* into the process of advancing research itself. Currently, many departments are in charge of R&D, especially development, in various parts of the NTT Group. Under those circumstances, the NTT laboratories are very special. Here, *special* refers to a researcher's way of thinking and the subject that the researcher is tackling—which is clearly different from development in general. Therefore, I think it is meaningful to go back to the starting point of the research and re-evaluate what role researchers should play and what research can only be done by NTT.

We have created many technologies so far. A recent example is our successful demonstration of wavelength-division-multiplexed optical transmission at 1 Tbit/s per wavelength over a long distance—a world first—by using digital signal processing technology and ultra-broadband optical front-end integrated device technology. This optical transmission technology enables transmission rates that are ten times the capacity—namely, 100 Gbit/s per wavelength—of current practical systems. It is therefore expected to achieve the high-capacity communications networks that will help expand Internet of Things and 5G services. Simply put, it has tremendous potential in terms of achieving the ultimate low-latency transmission in an end-to-end manner, which would enable 4K/8K video to be transmitted in real time without having to compress it. I have the feeling that this will lead to paradigm shifts in various industries.

The origin of such technology is basic research. That basic research leads to applied research, the fruits of which are further developed for practical use. That's why I want to enhance our basic research. On the basis of that, I think it is important to create a flow from basic research to practical development and then to commercialization of services and the creation of new business. This flow will allow our research to flourish in the form of *value creation* for the world, and that is exactly what I mean by "making the world smart."

Incidentally, software has been highlighted in many ways such as software-defined networking and open source software in the past several years; however, I think it is necessary to reaffirm the importance of hardware. That's because software runs and generates its value on innovative hardware. There are various limitations due to technical difficulties and costs, but there are some things only hardware can provide, such as ultra-wideband optical front-end integrated devices, and I believe that it is essential to produce such things and take up the challenge of improving them. I think that as part of the smart flow I mentioned before, it is necessary to view R&D in total, including not only software but also hardware.

We have been talking from a viewpoint of problem solving in society. However, I think that we must consider another viewpoint of growing a sense of happiness, too. Matters that generate a sense of happiness are not universal. For example, Japanese people think that sushi is delicious; but, many people in countries that do not like cold meals generally do not think it is delicious. However, people from such countries are increasingly visiting Japan and enjoying sushi. That situation shows that people's values can change through experience and be shared with others. I think there are many ways that people can share values, and sharing values has been my major research theme as a researcher, and it has also become a research policy. I'd be very happy if we could be involved in inspiring people and making them happy. And I think that hope will become one of the themes of our *smart* research.

From a global perspective, our current medium-term management strategy lays out "strengthening competitiveness of global business" and "globalization of R&D." We aim to enhance basic research as efforts to create innovative things and something entirely new, and accordingly, we have established a new research corporation, NTT Research, Inc., in Silicon Valley in the US. In addition to spreading the achievements of the NTT laboratories globally, we are also promoting the globalization of our R&D targets. The research themes originate not only in Japan but also all over the world.

Taking a global view of ideas for creating new technologies, services, and business for solving various problems scattered around the world, we are grasping the research themes that are revealed from that viewpoint. I believe the globalization of R&D is not only about expanding seeds that have grown domestically but also actively incorporating seeds that have grown around the world and those that can be expected to grow in the future.

Believe in one's identity while advancing diversity

—How were these values created?

I lived in New York, where people of many different cultures are gathered from around the world, until the second grade of elementary school. There were few Japanese there at that time, and it was difficult for children to develop their own identity in the community. In those environments, I had the experience of gradually opening my heart to others and being accepted by them. As for my research activities when I was in graduate school, I sometimes wondered what it is to be human and what research activities would be best to carry on with. At that time, I studied anthropology and learned that it was important to recognize that people have different values and senses of happiness. That recognition is at the root of my current stance.

In regard to R&D, there are various types of research in a wide range of fields that cannot be described in one word. Moreover, there are researchers involved in such research around the world. Under those circumstances, researchers should aim to pursue research with the pride and conviction that new services and value will not be created if they do not research this theme or have the attitude "Who will do this research if I don't do it myself?" At one time, there was an argument that we do not necessarily have to aim to be number one. That is still true and I think it is possible to create new value by thoroughly pursuing anything that anyone can think up. However, researchers tend to take pride in achieving things through difficult means. If the result is the same, it doesn't matter if it was difficult or easy to create.

I think whether the results of research really benefit the world is important. Many researchers don't actually mind struggling to solve difficult problems and even find it stimulating to do so. There is no doubt that they are all very hard workers. However, it is sometimes unrealistic to doggedly stick to a pursuit because doing so doesn't always lead to the happiness of society. I think that their efforts will be fruitful if researchers keep a broad view and do not lose sight of the goal of serving the world. That's why I want to stick to playing the role of giving advice—in the phase from basic research to applied research—on whether or not research will lead to the happiness of people in society, which is another need we must consider. And I think it would be of great value to NTT to deeply explore that direction.

On the contrary to what I said above, not all researchers take this viewpoint and I think it is impossible to force them to do so. Diversity is very important, and some people have exceptional talent. My duty is therefore to gather those people together and lead them to achieve the goals that are set.

—Since you have been a researcher yourself, you must have learnt many lessons. Would you like to say a word to your researchers?

My research theme when I joined NTT was satellite communications. I was really happy to work on a fantastic theme associated with the space. However, NTT changed its business model from owning communications satellites to leasing them from other companies. I was really shocked because I thought that it was a theme I could tackle over a lifetime. When I was pondering what to do in the future, a colleague mentioned that the research related to content was pretty close to what I was doing with satellites. Although I didn't really know how and where satellites and content could be connected, my colleague convinced me that it was better to research content from then on because the age of content was coming. With those words in mind, I was able to extend my research themes to IP (Internet protocol) television and our ultrahigh presence communications technology called "Kirari!".

As researchers, you may be forced to take an about-turn in the future. I must admit a research theme that lasts forever is great, very important, and worthwhile, but, one day, the theme may not be the target of research anymore. However, that does not mean that you are not needed anymore because there is no longer work to do. I believe that research is in the mindset, and themes will follow accordingly. The *mindset* in that sense means the intention of researchers, for example, the intention to invent and propose new principles, the intention to understand a certain phenomenon and clarify its mechanism, and the intention to create as a form what has never been created before, and these intentions do not depend on the research theme. I'd like you to continue to believe that as long as you maintain your own enthusiasm, you can find new themes wherever you look. If you think about how you apply your way of thinking, your approach, and your knowledge accumulated so far, you will see infinite possibilities and infinite themes. I want you to take up those challenges. You should believe in yourselves so that you can find new themes. I want you to reconsider, as a researcher, your identity, your existence value, and why you are here, and think seriously about what you need to do. There was a time when we decided our direction and goals, and everyone worked together toward those goals; however, now is the time to pursue various possibilities in many ways. Do not give up believing in yourself, your research theme, or the potential of your challenges. I want to create an environment for supporting that belief you should have in yourselves.

Interviewee profile

■ Career highlights

Katsuhiko Kawazoe joined NTT in 1987. He became Vice President of Research and Development Planning in 2008, head of NTT Service Evolution Laboratories in 2014, and head of NTT Service Innovation Laboratory Group in 2016. He assumed his present position in June 2018.

Ultrahigh-speed Transmission Technology for Future High-capacity Transport Networks

Yutaka Miyamoto, Shuichi Yoshino, and Akira Okada

Abstract

Ultrahigh-speed transmission technologies in radio and optical fiber transport systems are essential to accommodate the ever-increasing demand for bandwidth in future network infrastructure. Advanced digital modulation/demodulation techniques as well as ultrahigh-speed front-end integration technologies are optimized to fully exploit the characteristics of different types of transmission media such as air and optical fiber, considering novel degrees of freedom such as space division multiplexing. This article introduces state of the art research and development that achieves ultrahigh-speed communications at speeds of over 1 Tbit/s per carrier (over a hundred times the current speed) in both optical fiber transmission and radio transmission.

Keywords: transmission, digital modulation/demodulation, parametric optical amplification

1. High-capacity transport networks and applications of ultrahigh-speed communications

Common broadband network services such as video streaming and electronic commerce (e-commerce) are now available all over the world via personal computers (PCs) and smartphones in daily life. The novel transmission technologies have thus become essential for future network infrastructure in order to achieve further network service evolutions. The fifth-generation (5G) mobile communications service will start in fiscal year 2019, and broadband communications at a line rate up to 20 Gbit/s with low latency will be expected to support emerging new services such as self-driving vehicles and factory automation. Furthermore, it is expected that the application of new technologies such as machine learning and artificial intelligence will facilitate the emergence of new applications such as detailed weather forecasting and preventive medicine, thanks to the Internet of Things technology achieved through recent advances in cost-effective low-power semiconductor integrated circuits used in sensor technology. We believe that future transport networks will have to support the creation of such new application services supporting our daily life.

The application area of ultrahigh-speed transmission technology in today's high-capacity transport networks is shown in **Fig. 1**. In radio transmission, significant advances in digital modulation/demodulation techniques have been made in fixed microwave transmission systems, and these had been used to support long-haul core networks until the commercial installation of optical fiber transmission systems began in the 1980s [1]. Further advances have been made in these fixed microwave transmission system technologies to enable economical link systems in areas where it is difficult to install a wired cable transport system.

In addition, dramatic technological advances have been made in mobile communications, achieving high-speed wireless local area networks and mobile phones in the last quarter of a century. Today, wireless access services using PCs and smartphones (4G) with a throughput of at least 1 Gbit/s have spread throughout the world. Furthermore, next-generation 5G systems will offer faster wireless access with the high reliability and low latency required for self-driving

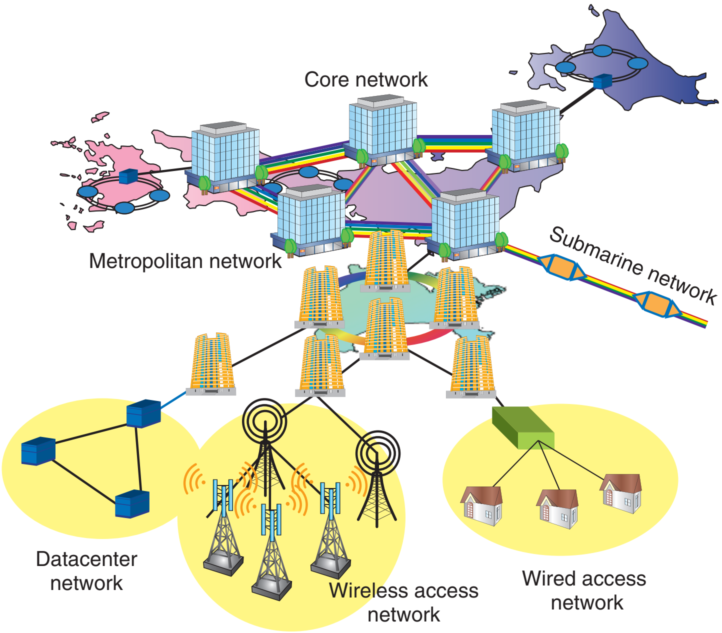

Fig. 1. Application area of ultrahigh-speed transmission technology.

vehicles and factory automation.

An ultrahigh-speed optical fiber transmission system was first installed in NTT's core network in the 1980s, and remarkable progress has been made over the last 40 years. Today, optical fiber is widely used for transoceanic systems over 10,000 km, long-haul national backbone networks, metropolitan networks, and access networks. Optical fiber transmission systems have also become indispensable recently for increasing the capacity of networks such as datacenter (DC) networks and mobile backhauls. Optical fiber transmission systems have so far mostly used single-mode fiber (SMF) as a transmission medium. SMF is designed to have only one optical waveguide (core) per fiber supporting a single waveguide mode. Recent long-haul core networks support a capacity in excess of 10 Tbit/s per fiber by using 100-channel wavelength division multiplexing (WDM) of 100-Gbit/s channels [2]. Furthermore, low-power optical communications with a compact configuration and a channel capacity over 200 Gbit/s have recently been introduced in DC interconnection networks [3].

2. Technical challenges in ultrahigh-speed communications technology

This section describes the common technical challenges in introducing ultrahigh-speed communications technologies in both radio transmission systems and optical fiber transmission systems. The system capacity C of a communications system is generally expressed by the following equation according to Shannon's well-known theorem:

$$C = N \cdot B \cdot log\,(1 + SNR),$$

where N represents the number of multiplexed channels, B represents the signal bandwidth, and SNR represents the signal-to-noise ratio. There are three major approaches to improving the system capacity C of a communications system as expressed by this equation:

Approach 1: Increase the symbol rate by expanding the signal bandwidth B of each channel.

Approach 2: Improve the SNR by reducing noise in the system and/or increasing the signal power, or by adopting a digital modulation technique such as quadrature amplitude modulation (QAM)* that is more efficient than binary modulation.

Approach 3: Improve the channel capacity by using a frequency or spatial degree of freedom to achieve higher multiplicity (increasing N).

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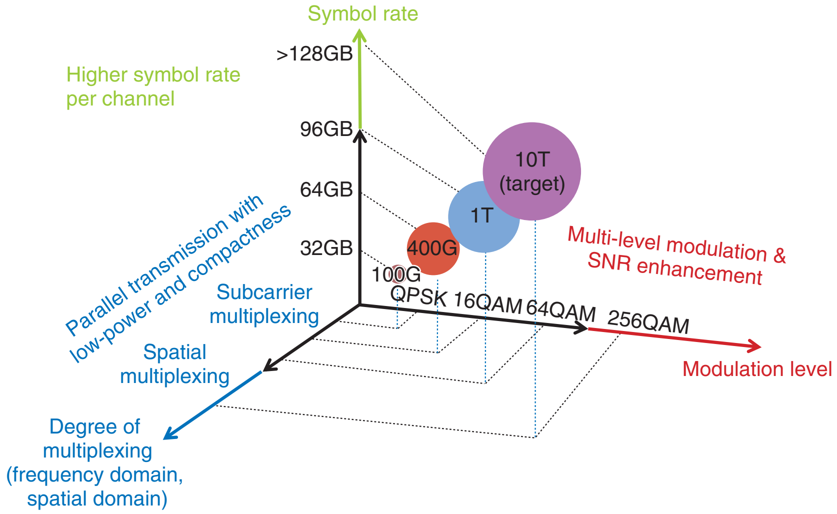
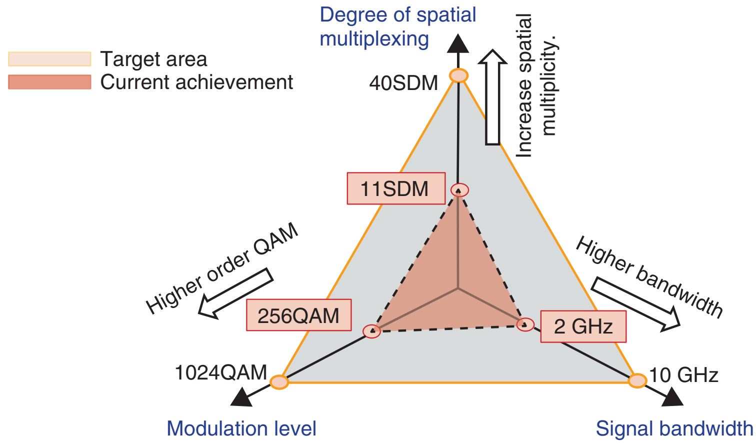
* QAM: A highly efficient digital modulation scheme whereby the amplitude and phase of a signal's electrical field are modulated to multiple signal levels.



(a) Optical fiber transmission



(b) Millimeter-wave radio transmission

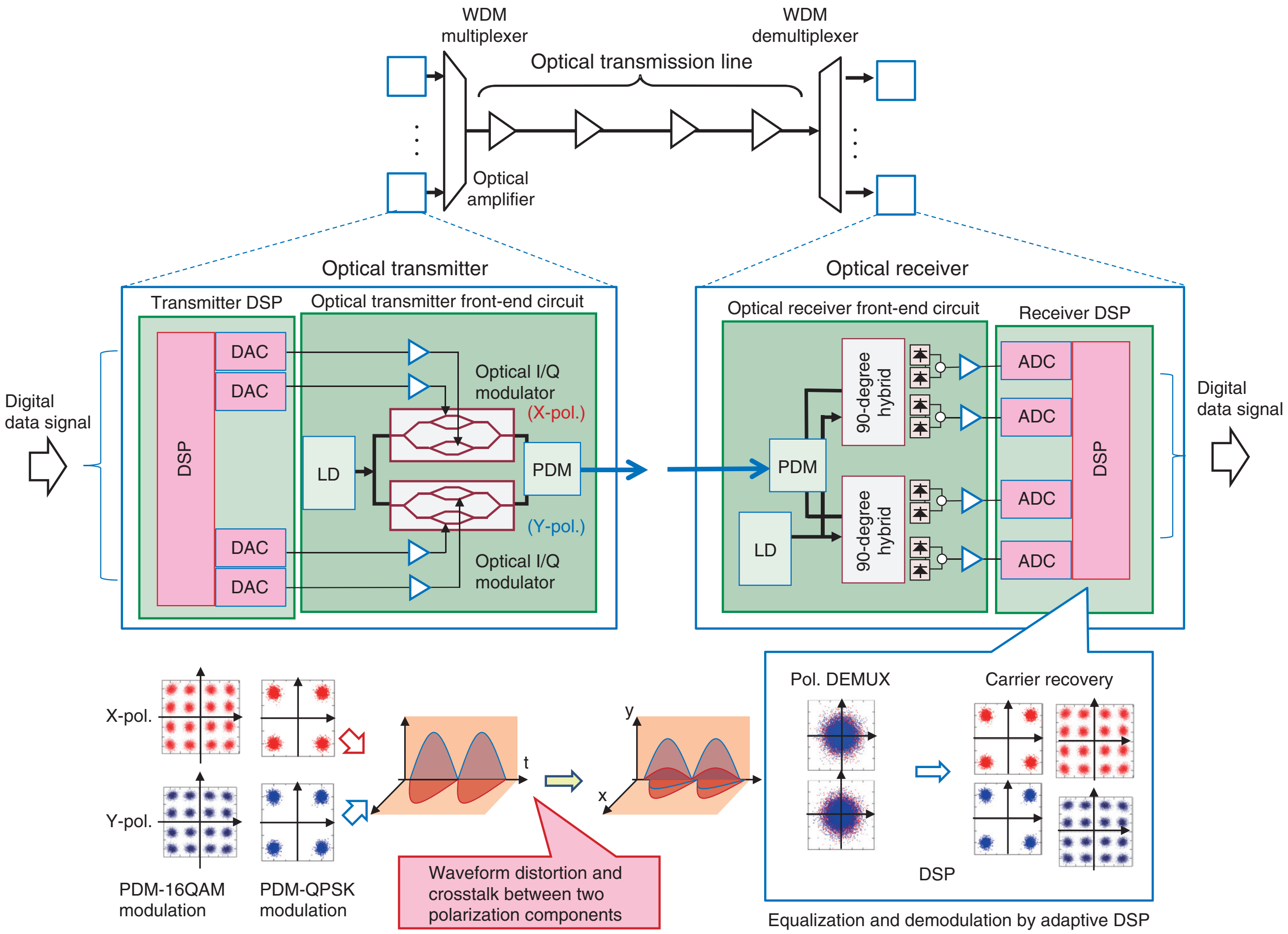
QPSK: quadrature phase-shift keying
SDM: space division multiplexing

Fig. 2. Three approaches in ultrahigh-speed communications.

To increase the channel speed in both wireless and optical fiber communications, it is very important to choose the right combination of the feasible abovementioned approaches considering their application area and the maturity of the technologies.

The future technical trends of the abovementioned approaches in line-of-sight millimeter-wave radio transmission and optical fiber transmission are shown in **Fig. 2**. In the case of using single-channel polarization-division multiplexed (PDM) quadrature phase-shift keying (QPSK) (Approach 1 only) to realize channel capacities over 1 Tbit/s, it is necessary to achieve a symbol rate of at least 300 Gbaud. However, it is very difficult to achieve such a high symbol rate over 300 Gbaud using the latest front-end devices and digital signal processing (DSP) circuits with analog-to-digital converter (ADC) circuits and digital-to-analog converter (DAC) circuits. We therefore need to reduce the required symbol rate by adopting higher-order QAM and/or by using subcarrier multiplexing in the frequency or spatial domain.

An example of the latest digital coherent optical



DEMUX: demultiplexer
IQ: in-phase and quadrature
LD: laser diode
Pol.: polarization

Fig. 3. Example configuration of digital coherent optical transceiver circuit in an optical fiber transport system.

transceiver circuit configuration in an optical fiber transmission system is illustrated in **Fig. 3** [2, 3]. In this system, each channel is modulated in PDM-QPSK format, and approximately 100 channels of 100-Gbit/s optical signals are wavelength-division-multiplexed to form a 10-Tbit/s aggregate capacity signal and transmitted through an optical inline amplified link over 1000 km.

Here, the optical transmitter consists of a transmitter DSP circuit and an optical transmitter front-end circuit. Each polarization component from a continuous-wave signal laser diode (LD) is independently modulated in QPSK format at a symbol rate of the order of 32 Gbaud, and 100-Gbit/s PDM-QPSK signals (approximately 64 Gbit/s per polarization in gross capacity with error-correcting coding at a coding rate of $R = 5/6$) can be generated. If the modulation scheme is adaptively changed to 16QAM, it is possible to double the channel capacity to 200 Gbit/s at the same symbol rate.

Similarly, the optical receiver consists of a receiver DSP circuit and an optical receiver front-end circuit. An intradyne reception of PDM-QPSK signals is performed using a wavelength-tunable local oscillating LD that has a frequency offset within a few gigahertz. Four lanes of received electrical tributary signals are fed to ADCs, and linear waveform distortions of transmitted signals after the optical fiber transmission are digitally equalized to demodulate the QPSK (or 16QAM) signals. Finally, the error correcting

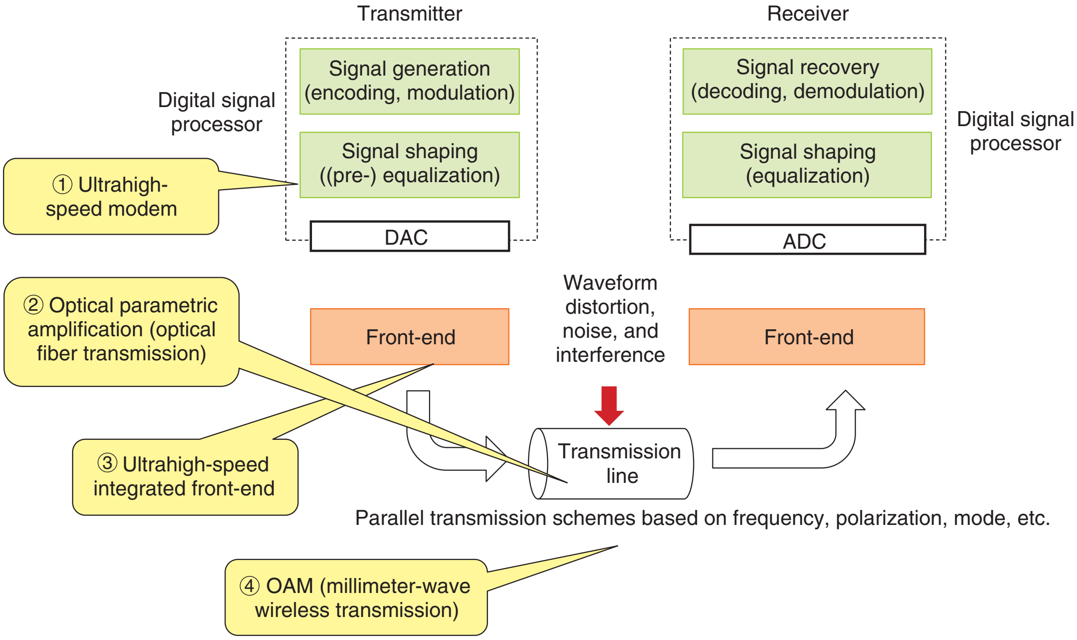


Fig. 4. Key technologies to achieve future ultrahigh speeds for millimeter-wave radio transmission and optical fiber transmission.

code recovers the original data bit stream. In this case, the throughput in the DSP circuit exceeds 2 Tbit/s (≈8×2×(6/5)×100 Gbit/s) between the DSP circuit part and the DAC/ADC circuit part, when the channel capacity is 100 Gbit/s assuming 8-bit quantization, a sampling rate of two samples per symbol, and an error correction coding rate of $R = 5/6$.

In order to implement a compact and cost-effective DSP circuit, it is preferable to integrate the DAC/ADC circuit part and the DSP circuit part on a single-chip large-scale integrated (LSI) circuit. Furthermore, it is essential to suppress the skew of the four parallel broadband analog electrical signals (in-phase and quadrature signal components for each of the X- and Y-polarization planes) between the DSP-ASIC (application-specific integrated circuit) and optical front-end circuits for high-quality digital modulation and demodulation.

3. Fundamental technologies for ultrahigh-speed communications infrastructure

The Feature Articles in this issue focus on the four fundamental technologies of ultrahigh-speed transmission to achieve a capacity of 1 Tbit/s (**Fig. 4**), and they introduce the current status and future prospects of these technologies.

3.1 Ultrahigh-speed digital modulation/demodulation circuit technology

The ultrahigh-speed transmission technology used in digital modulation and demodulation circuits has common technical issues for both optical fiber transmission systems and radio transmission systems. The article “Ultrahigh-speed Optical Communications Technology Combining Digital Signal Processing and Circuit Technology” [4] discusses the latest achievements relating to the required functions of ultrahigh-speed digital modulation/demodulation circuits with capacities of over 1 Tbit/s per wavelength, especially in optical fiber transmission systems. In general, higher-order QAM digital modulation and demodulation require a higher SNR and more precise DSP calibration techniques for simple and stable operation. Here, we discuss the effectiveness of a novel coded modulation that makes full use of the features of higher-order QAM digital modulation.

3.2 Low-noise high-power parametric amplifier relay technology

Low-noise high-power parametric amplification technology is promising for reducing system noise, as needed for higher-order QAM signal transmission. Optical signal processing based on the parametric amplification greatly reduces the required complexity of DSP for high-speed higher-order QAM signal transmission.

When the gate length of CMOS (complementary metal oxide semiconductor) LSI circuits is reduced to just a few nanometers (about 10 monolayers of silicon atoms), it is predicted that the conventional scaling law in terms of transistor switching speeds and power consumption (namely Moore's Law) will gradually saturate. To achieve higher channel speeds, this situation will naturally require new system architectures and novel technologies to reduce the amount of DSP and power consumption. In future optical nodes, parametric optical amplifiers will achieve simultaneous coherent optical signal processing of WDM high-speed channels to reduce system noise and the required DSP complexity of waveform distortion compensation of high-speed channels. They are also expected to reduce the system's overall power consumption. The article "Low-noise Amplification and Nonlinearity Mitigation Based on Parametric Repeater Technology" [5] in this issue introduces a low-noise, highly efficient parametric optical amplification system that uses PPLN (periodically-poled Lithium Niobate) crystals developed at NTT's laboratories.

3.3 Ultrahigh-speed optical front-end integration technology

The article "Ultrahigh-speed Optical Front-end Device Technology for Beyond-100-GBaud Optical Transmission Systems" [6] introduces ultrahigh-speed device interconnections between the front-end circuits and DSP circuits. The novel architecture of integrated front-end circuits equipped with an analog multiplexing/demultiplexing function in the front-end circuits can relax the required operation speed of the DAC/ADC in DSP circuits. It also reduces the input and output speed at the front-end module interface to achieve stable interconnections between front-end circuits and DSP circuits. We present the latest performance results of the proposed optical front-end integrated technology for optical fiber communications at symbol rates in excess of 100 Gbaud.

3.4 Ultrahigh-speed technology based on orbital angular momentum mode multiplexing

The article "Toward Terabit-class Wireless Transmission: OAM Multiplexing Technology" [7] introduces novel spatial multiplexing technology for realizing line-of-sight millimeter-wave wireless communications at speeds on the order of 1 Tbit/s. A new spatial degree of freedom based on the orbital angular momentum (OAM) of an electromagnetic field is introduced to increase the spatial multiplicity.

In recent research on optical fiber transmission, mode-multiplexed optical transmission technology using multiple orthogonal waveguide modes was proposed to increase the transmission capacity beyond the physical limit of existing SMF. It has recently been shown that multiple-input multiple-output (MIMO)-DSP technology has great potential to realize long-haul inline amplified transmission over 6000 km [8]. In wireless systems, on the other hand, it is generally impossible to define orthogonal waveguide modes as used in optical fiber, although conventional MIMO spatial multiplexing based on transmission path differences is widely used in commercial wireless communications.

A novel spatial multiplexing scheme using OAM was recently proposed as a way to achieve 100-Gbit/s channel transmission in millimeter-wave wireless communications [9]. This demonstration attracted much attention as a candidate for further increasing the speed of backhaul networks in 5G and post-5G applications. To achieve such high-speed mode-multiplexed transmission systems, it is essential to effectively implement DSP circuits considering the tradeoff between the DSP complexity and reliable dynamic characteristics to accommodate high-speed channel fluctuations in each transmission line (free space, optical fiber, etc.). Further progress in advanced DSP architecture and novel combinations of the abovementioned fundamental technologies are expected.

4. Future prospects

This article introduced the latest ultrahigh-speed communications technologies and future trends to realize a channel capacity over 1 Tbit/s in future transport networks. Further advances are expected in highly efficient DSP technologies for ultrahigh-speed channel transmission with careful consideration of practical DSP complexity economically implemented in single-chip LSI circuits. In millimeter-wave communications, a new degree of freedom offered by the OAM of electromagnetic waves in free space is expected to increase the channel speeds to over 1 Tbit/s. In optical fiber communications, long-haul transmission of high-speed channels beyond 1 Tbit/s will be achieved by using a suitable combination of advanced DSP functions and integrated optical front-end technology. Optical parametric amplifier technology and spatial multiplexing technology are promising for achieving further increases in the channel speed while maintaining the current DSP complexity and power consumption in optical fiber communications. Through continuous efforts in research and development and timely commercialization of these new technologies, terabit-per-second-class signals will be able to be easily handled in future transport networks.

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Yutaka Miyamoto

Senior Distinguished Researcher, Director, Innovative Photonic Network Research Center, NTT Network Innovation Laboratories.

He received a B.E. and M.E. in electrical engineering from Waseda University, Tokyo, in 1986 and 1988, and a Dr. Eng. from the University of Tokyo. He joined NTT Transmission Systems Laboratories in 1988, where he engaged in research and development of high-speed optical communications systems including the first 10-Gbit/s terrestrial optical transmission system (FA-10G) using EDFA (erbium-doped optical fiber amplifier) inline repeaters. He was with NTT Electronics Technology Corporation between 1995 and 1997, where he engaged in the planning and product development of high-speed optical modules at data rates of 10 Gbit/s and beyond. Since 1997, he has been with NTT Network Innovation Labs, where he has been researching and developing optical transport technologies based on 40/100/400-Gbit/s channels and beyond. He has been investigating and promoting scalable optical transport networks with Pbit/s-class capacity based on innovative optical transport technologies such as digital signal processing, space division multiplexing, and cutting-edge integrated devices for photonic pre-processing. 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).

Shuichi Yoshino

Director, General Manager, NTT Network Innovation Laboratories.

He received a B.E. and M.E. in mechanical engineering from Kanazawa University in 1990 and 1992. He joined NTT in 1992 and worked on the development of a satellite Internet system and wireless networking technologies. He has contributed to the practical application of active radio frequency identification devices for logistics and wireless access technologies for gas meter reading systems.

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Ultrahigh-speed Optical Communications Technology Combining Digital Signal Processing and Circuit Technology

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Abstract

This article introduces ultrahigh-speed optical communications technology that achieves the optical transport networks needed to support an advanced information society. Most data traffic is carried on the Ethernet; 400G Ethernet has recently been standardized, and discussions have also started on standardizing signal speeds in excess of 1 Tbit/s. This technology is used to economically transmit high-speed client signals such as Ethernet signals on optical fiber networks. The combination of advanced digital signal processing and ultrahigh-speed circuit technology can greatly improve the speed and quality of optical signals and is expected to result in cost-efficient ultrahigh-speed optical communications at rates in excess of 1 Tbit/s per channel.

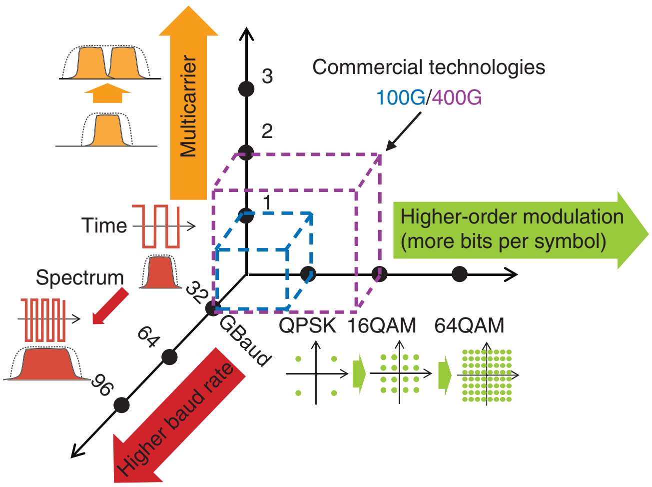
Keywords: optical communications, digital signal processing, high-speed Ethernet

1. Introduction

Ultrahigh-speed optical communications technology is the fundamental technology that determines the transmission performance of optical networks. In a backbone network, multiple ultrahigh-speed client signals such as 400G Ethernet (400GE; standardized in 2017) are accommodated in high-speed optical channels based on digital coherent transmission technology [1], and multiple high-speed optical channels are combined by wavelength division multiplexing (WDM) to implement a long-distance high-capacity optical network. Meanwhile, the rate of internal data transmission between servers in datacenters that support various services such as social networking and video distribution services is becoming very large, and so is the demand for communications between multiple datacenters. Compared with the backbone network, the transmission distances are shorter, but greater economy is required, and high-speed data transmission is implemented by employing a technique called intensity-modulation direct-detection (IM-DD), which has a simple transceiver configuration.

2. Technical issues in increasing the optical signal data rate

Optical communications technology capable of accommodating 100-Gbit/s and 400 Gbit/s client signals per channel has already been put to practical use [2]. During the Ethernet standardization activities, discussions were initiated and are continuing on the next transmission speed standard, with 800 Gbit/s and 1.6 Tbit/s being cited as possible candidates. In the future, optical networks are expected to accommodate



QAM: quadrature amplitude modulation
QPSK: quadrature phase-shift keying

Fig. 1. Three key elements of high-speed optical signals.

high-speed client signals at speeds of over 1 Tbit/s per channel.

The three key elements of high-speed optical signals are shown in **Fig. 1**. Conventional IM-DD systems transmit information using binary light intensity signals (either on or off), but by using the digital coherent technique shown in **Fig. 2**, it is now possible to use optical amplitude and phase information to transmit signals with four or more values per pulse. In addition, by performing digital signal processing in the transceiver, it is possible to equalize and compensate for wavelength deformation caused by polarization separation and wavelength dispersion and polarization mode dispersion that occur inside the optical fibers, resulting in substantial increases in the transmission range and data transmission rate.

Currently, practical optical signals carrying data at a rate on the order of 100 Gbit/s per channel are achieved by using polarization multiplexing to combine 4-value quadrature phase-shift keying (QPSK) signals at a rate of 32 Gbaud. In addition, 400-Gbit/s optical signals are achieved by using two carriers (wavelengths) to carry two 16-quadrature amplitude modulation (QAM)*1 polarization multiplexed signals at 32 Gbaud in a single transmission channel.

There are also three key elements for speeding up optical signals (Fig. 1). The first is to use a higher baud rate (light pulse speed). If the baud rate is increased, this provides a corresponding increase in the transmission rate per wavelength. If signals have the same number of bits per symbol, then the baud rate can be increased without any excessive deterioration of reception sensitivity, but in order to transmit and receive these high baud rate signals, it is necessary to use devices that are capable of operating at high speed, including electrical devices such as digital-to-analog converters (DACs), analog-to-digital converters (ADCs), and optical devices such as optical modulators and balanced photo detectors (BPDs). Also, in the frequency domain, the bandwidth occupied by optical signals increases in proportion to the baud rate. This means that fewer signals can be combined by WDM, so unless this approach is combined with the use of a higher number of bits per symbol as described later, the overall capacity of the transmission system will not increase.

The second element is the use of more bits per symbol. By increasing the number of optical amplitude levels and phases used for signal transmission, it is possible to increase the number of bits that can be transmitted in a single optical pulse. For a given baud rate, the transmission speed improves in proportion to the number of bits per symbol*2. With more bits per symbol, devices such as DACs and ADCs must have greater resolution and linearity, and the required signal-to-noise ratio (SNR) also increases. This

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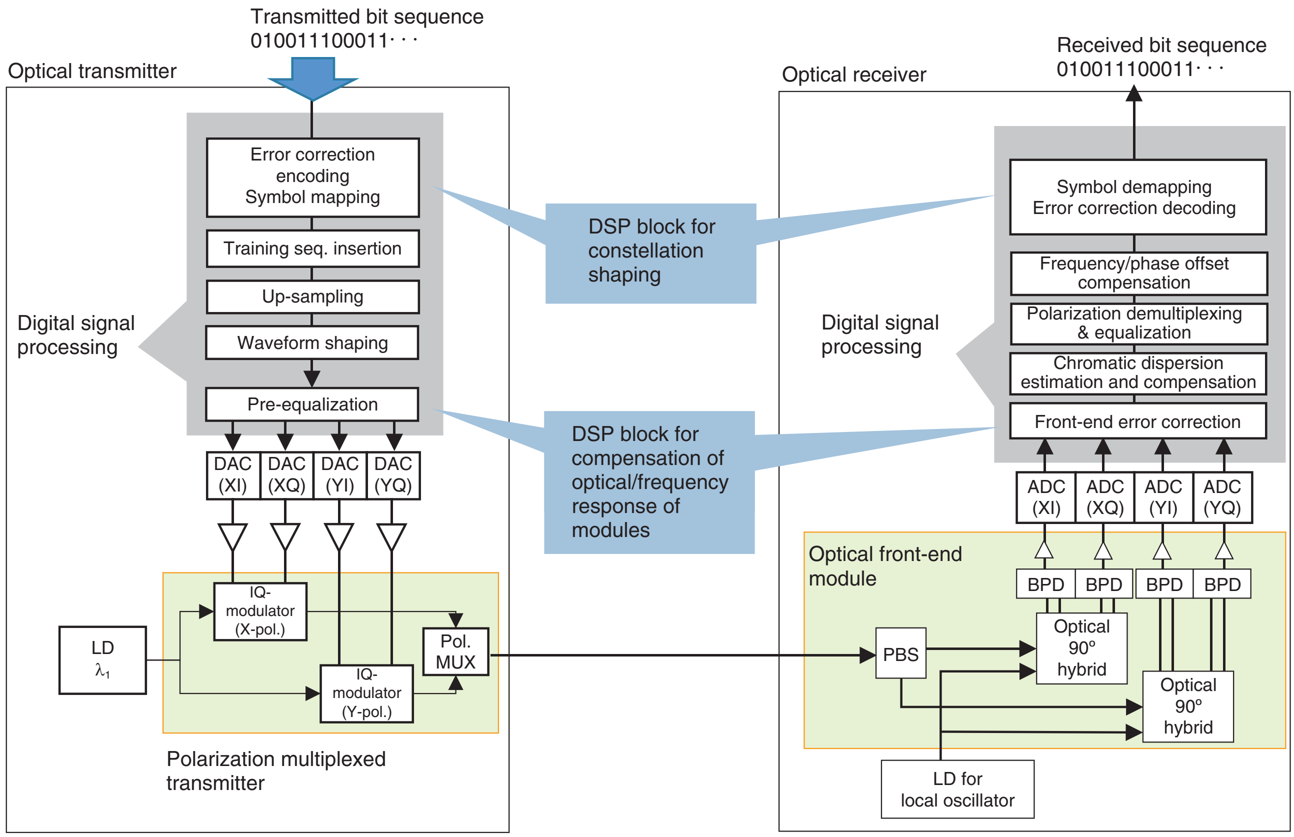
*1 QAM: A highly efficient digital modulation scheme where data are transmitted as a series of multilevel codes by modulating the amplitude and phase of a carrier signal at multiple levels.



ADC: analog-to-digital converter
BPD: balanced photo detector
DAC: digital-to-analog converter
DSP: digital signal processor
IQ: in-phase and quadrature
LD: laser diode
MUX: multiplexer
PBS: polarization beam splitter
Pol.: polarization

Fig. 2. Schematic diagram of coherent optical transceiver.

decreases the maximum transmission distance, and reduces the resilience to signal distortion. Although QAM with a square constellation is currently used, it is possible to improve the required SNR by using a modified constellation.

The third element is the use of multicarrier transmission. By configuring one channel from optical signals of multiple wavelengths (carriers), it is possible to increase the capacity per channel in proportion to the number of carriers. This is an effective method for configuring a logical high-speed channel in an optical network. For example, it is possible to achieve a channel speed of 1 Tbit/s by bundling five 200-Gbit/s per wavelength optical wavelengths at different wavelengths into a single channel. However, since this increases the required number of transceivers, the abovementioned increases in baud rate and number of bits per symbol result in a higher transmission rate per wavelength but require the application of multicarrier technology that takes transmission performance and economy into consideration.

Thus, in order to attain ultrahigh-speed optical transmission at rates in excess of 1 Tbit/s per channel, it is essential to increase the baud rate and the number of bits per symbol, and while developing high-speed devices, it is necessary to use highly sensitive digital signal formatting and signal processing technology that enable the device requirements to be relaxed.

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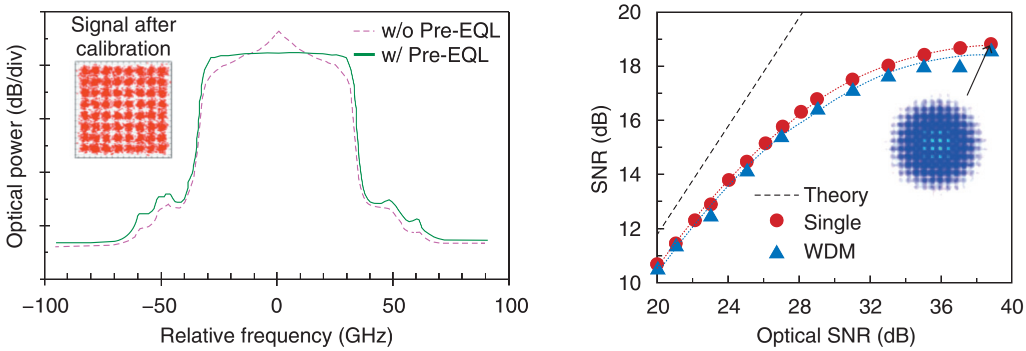
*2 Improvement proportional to bits per symbol: For example, the number of bits per symbol is doubled by switching from QPSK with a four-point constellation ($4 = 2^2$) to 16QAM with a 16-point constellation ($16 = 2^4$); however, switching from 16QAM to 64QAM only increases the number of bits per symbol by a factor of 1.5 (from 4 to 6).



(a) Constellation and optical spectrum of calibrated 64-Gbaud 64QAM signal

(b) Evaluation results of constellation-shaped 82-Gbaud 256QAM signal

EQL: equalization

Fig. 3. Experimental results employing calibration technology and constellation shaping.

3. Digital calibration technology and high-sensitivity technology to maximize device performance

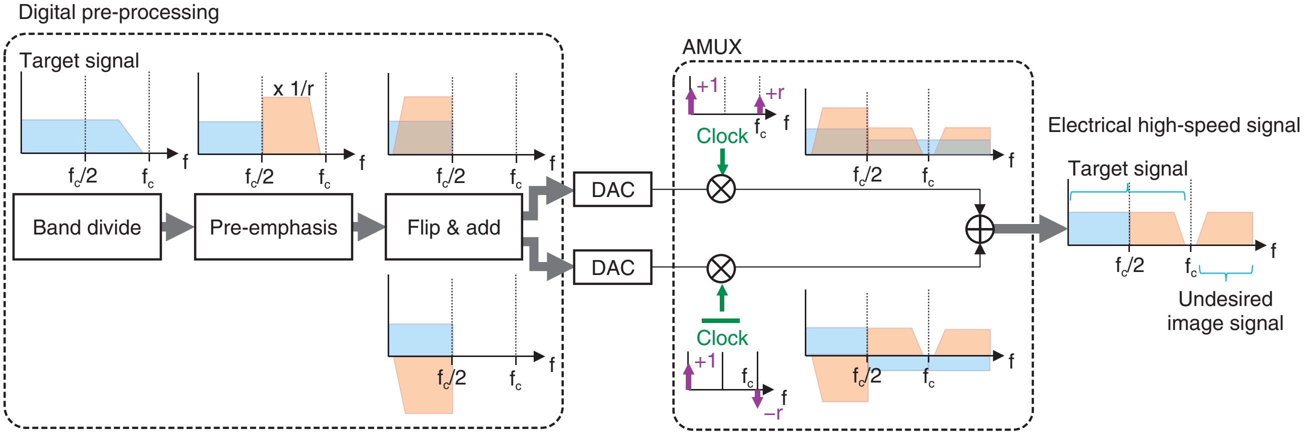
Signal degradation may occur when transmitting and receiving high-speed signals, even if the bandwidth of the electrical device or optical device meets the respective requirements. For example, as shown in Fig. 2, a digital coherent transmitter requires four DACs and two IQ (in-phase and quadrature) modulators for each polarization component. The receiving side requires four BPDs and four ADCs. Due to differences such as variations within manufacturing tolerances, the characteristics of these devices and the connections between them may not necessarily be uniform when they are all interconnected. These sorts of errors can have a major impact on the signal quality of high baud rate signals and signals with a large number of bits per symbol.

At our laboratory, we have managed to achieve substantial improvements in signal quality by digitally correcting device imperfections on the receiving side, and by using digital signal processing on the transmitting side to perform ultra-precise pre-equalization and calibration of the frequency characteristics and variation of devices in the transmitter. The optical spectrum of a 64-Gbaud 64QAM signal before and after calibration is shown in **Fig. 3(a)**. Pre-equalization smooths out the optical spectrum and improves its quality so that the indistinct signal constellation is resolved into a set of 64 clearly distinguishable points [3].

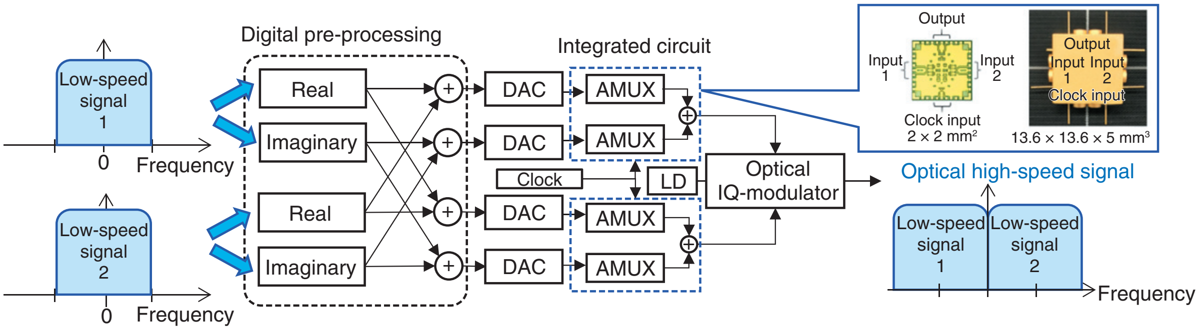
Also, with regard to the loss of sensitivity at a higher number of bits per symbol, we are studying how the signal constellation can be adapted in order to increase the signal sensitivity. Conventionally, multilevel QAM signals such as QPSK, 16QAM, and 64QAM have used signal constellations in which every point appears with equal probability. Although a multilevel QAM signal can be generated from the original bit sequence by using simple mapping and demapping processes, this does not yield an optimal signal constellation from an information theoretical point of view.

Attention has recently been focused on information-theoretical signal point-shaping techniques that can be used to achieve near-optimal signal constellations by arranging the constellation points of multilevel QAM signals based on probability distributions. Although this technique requires dedicated mapping and demapping processes, it enables the same number of data bits to be transmitted with a lower minimum SNR than that of multilevel QAM. Also, since the number of data bits to be transmitted can be changed by changing the probability distribution of constellation points without changing the base multilevel QAM signal, there is no need to modify the signal processing algorithm used for modulation and demodulation.

Our laboratory has conducted a successful test demonstration of 800 Gbit/s per wavelength transmission by using this pre-equalization calibration technique and 256QAM-based constellation shaping as shown in **Fig. 3(b)** [4]. With this technique, an optical network can use one or two wavelengths to accommodate client signals of 800 Gbit/s and 1.6 Tbit/s,



(a) Scheme using spectrum flip processing



(b) Scheme using addition/subtraction of low-speed signal

Fig. 4. Bandwidth doubling technologies using digital pre-processing and AMUX circuit.

which are candidate data rates for the next-generation Ethernet standard.

4. Bandwidth doubling technology for high-speed signal generation

One of the most important devices for generating high-speed optical signals is the DAC. DACs are integrated with digital signal processing LSIs (large-scale integrated circuits), but the analog bandwidth of DACs fabricated using Si CMOS (silicon complementary metal oxide semiconductor) is currently around 40 GHz. While the above calibration technique enables some correction, it becomes a bottleneck at high baud rates beyond 100 Gbaud. Our laboratory proposed bandwidth doubling technology that can double the analog bandwidth of a DAC. This technology involves preliminary signal processing of the desired wideband signal and outputting signals from two DACs. Using an analog multiplexer (AMUX) circuit [5] to combine these signals makes it possible to generate high-speed signals with twice the bandwidth.

We proposed the two bandwidth doubling methods shown in **Fig. 4**, and by applying these two methods to digital coherent transmission technology, we conducted an experimental demonstration of ultrahigh baud rate signal transmission using DACs with a 32-GHz analog bandwidth. We show in **Fig. 5(a)** the results of a transmission experiment using a 120-Gbaud signal generated using the spectral method shown in Fig. 4(a). In this experiment, we successfully transmitted data at a net rate[*3] of 600 Gbit/s per wavelength over a long distance of approximately

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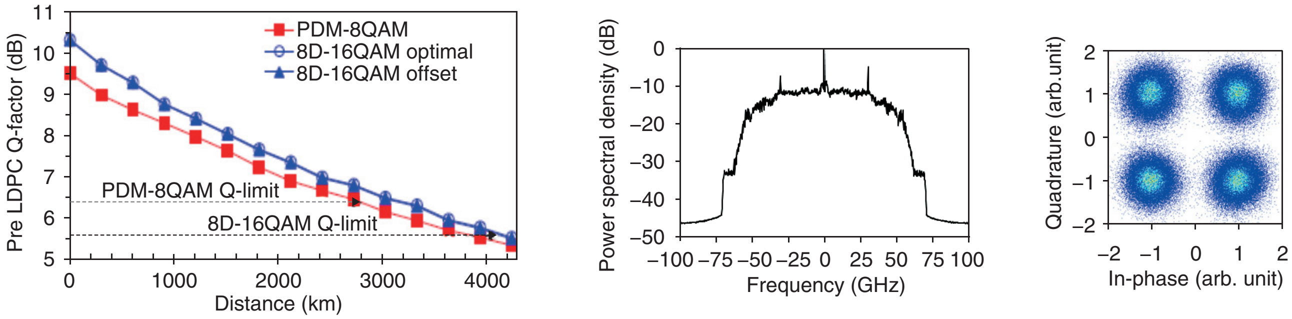
[*3] Net rate/line rate: The net rate represents the number of data bits transmitted per second as an optical signal. The line rate refers to the entire data signal, including signals for supervisory control and redundant bits for error correction.



(a) Transmission experiment result of 120-Gbaud signal using spectrum flip processing (net rate: 600 Gbit/s)

(b) 120-Gbaud QPSK signal generation using addition/subtraction of low-speed signal

LDPC: low-density parity check

Fig. 5. High-speed signal experiments using bandwidth doubling technologies.

4000 km [6]. Also, for the addition/subtraction processing method shown in Fig. 4(b), we made a prototype circuit integrated with two AMUX circuits, and we successfully generated 120-Gbaud QPSK signals as shown in **Fig. 5(b)** [7].

In theory, it is difficult to generate high-quality signals at 100 Gbaud or above using 40-GHz DACs, because the DACs require a bandwidth of at least half the baud rate. With our technique, it is possible to extend the bandwidth of existing DACs, enabling the signal baud rate to be increased. In addition, by combining the abovementioned calibration and sensitivity enhancement techniques, we have found that it is possible to achieve ultrahigh-speed signal transmission at over 1 Tbit/s per wavelength without resorting to multicarrier technology [8].

5. Application of ultrahigh-speed optical communications technology to short-distance communications

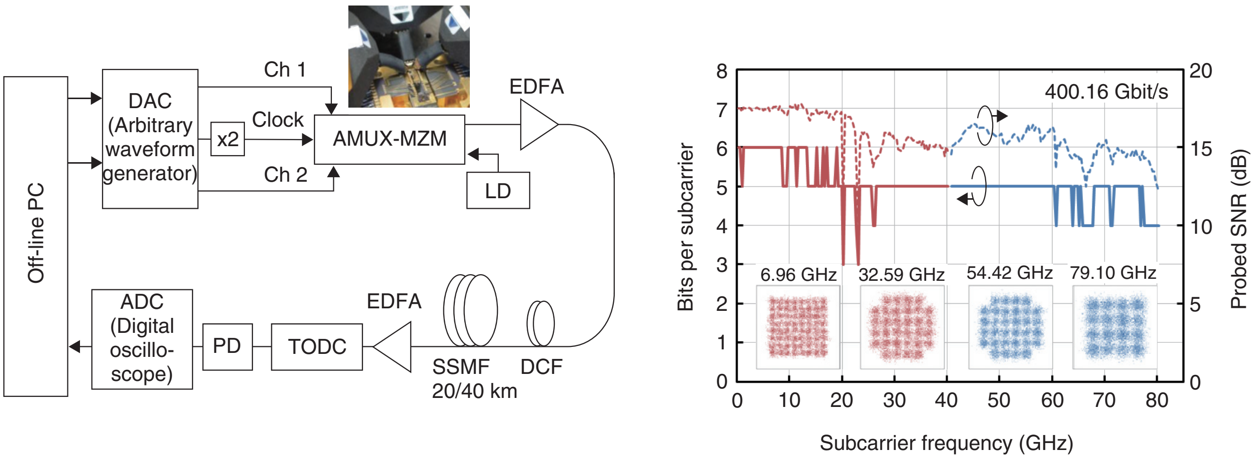
The simple and highly economical system configuration of the IM-DD method has attracted attention as an optical communications technique for short-distance communications on the order of a few tens of kilometers at most, where most traffic occurs between servers or between datacenters. The recently standardized 400GE system uses PAM4 (4-level pulse amplitude modulation) to produce four parallel 100-Gbit/s signals per wavelength and thus requires four sets of transceiver equipment. At our laboratory, we have performed successful short-distance transmissions over 20 km at a bit rate of 400 Gbit/s using a single transceiver by combining bandwidth doubling technology with an ultra-wideband indium phosphide (InP) modulator [9, 10]. This is the world's highest transmission rate for IM-DD using a single wavelength and a single polarization.

The results of this transmission test are shown in **Fig. 6**. In this experiment, we used an InP optical modulator with an exceptionally wide bandwidth together with a bandwidth doubler to generate a wideband electrical signal and were able to generate optical signals while maintaining the wide bandwidth of the electrical signal. Also, by using DMT (discrete multitone) as the modulation method, we generated 256 subcarrier signals by digital signal processing, and by allocating appropriate signal bits to each carrier according to the frequency characteristics of the electrical and optical devices, we achieved near-optimal bit allocation.

For example, as shown in Fig. 6(b), a high-SNR 6.96-GHz subcarrier is used for 64QAM signals, and a low-SNR 9.10-GHz subcarrier is used for 16QAM signals. The use of bandwidth doubling technology and a wideband modulator has made it possible to allocate even multilevel signals such as 16QAM to the high frequency domain. With this technology, it is expected that transmission rates of over 400 Gbit/s per wavelength can be achieved by IM-DD with a simple and economical transceiver configuration.

6. Summary

In this article, we introduced ultrahigh-speed optical transmission technology that combines digital



(a) Setup of 400-Gbit/s IM-DD transmission experiment

(b) Signal quality of 400-Gbit/s signal after 20-km transmission

DCF: dispersion compensation fiber
EDFA: erbium-doped fiber amplifier
MZM: Mach-Zehnder modulator
PC: personal computer
PD: photodiode
SSMF: standard single-mode fiber
TODC: tunable optical dispersion compensator

Fig. 6. Short reach application of digital-preprocessed analog-multiplexed DAC technology.

signal processing and high-speed circuit technology to achieve optical networks that will form the infrastructure of an advanced information society. We have shown that this technology is capable of ultra-high-speed optical transmission at over 1 Tbit/s per wavelength. In the future, we will keep working on improving the speed and will continue with our research and development so that this technology can provide a highly reliable communications infrastructure.

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Low-noise Amplification and Nonlinearity Mitigation Based on Parametric Repeater Technology

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Abstract

Digital coherent technology has advanced greatly in recent years. Further enhancement of its potential will require a breakthrough in both electrical digital signal processing and innovative technologies that exploit the coherency of light. In this article, we describe repeater technology that uses optical parametric amplification (OPA) to minimize degradation in the signal-to-noise ratio in optical transport systems. OPA can potentially achieve low-noise amplification and mitigate nonlinear impairments.

Keywords: nonlinear optics, optical parametric amplification, optical phase conjugation

1. Introduction

The recent advances in digital coherent technology have increased the capacity of optical communications systems by improving spectral efficiency. According to Shannon's Theory, a signal must have a high signal-to-noise ratio (SNR) if we are to achieve a system with high spectral efficiency. However, it has been pointed out that any attempt to improve the SNR is limited due to the accumulation of noise arising from optical amplifiers and signal waveform distortion (nonlinear impairments) caused by the nonlinear effect in the optical transmission fiber itself (**Fig. 1(a)**) [1]. New technologies designed to overcome this limit are now required if we are to improve the SNR in optical transport systems.

2. Optical parametric amplification technology based on periodically poled lithium niobate (PPLN) waveguides

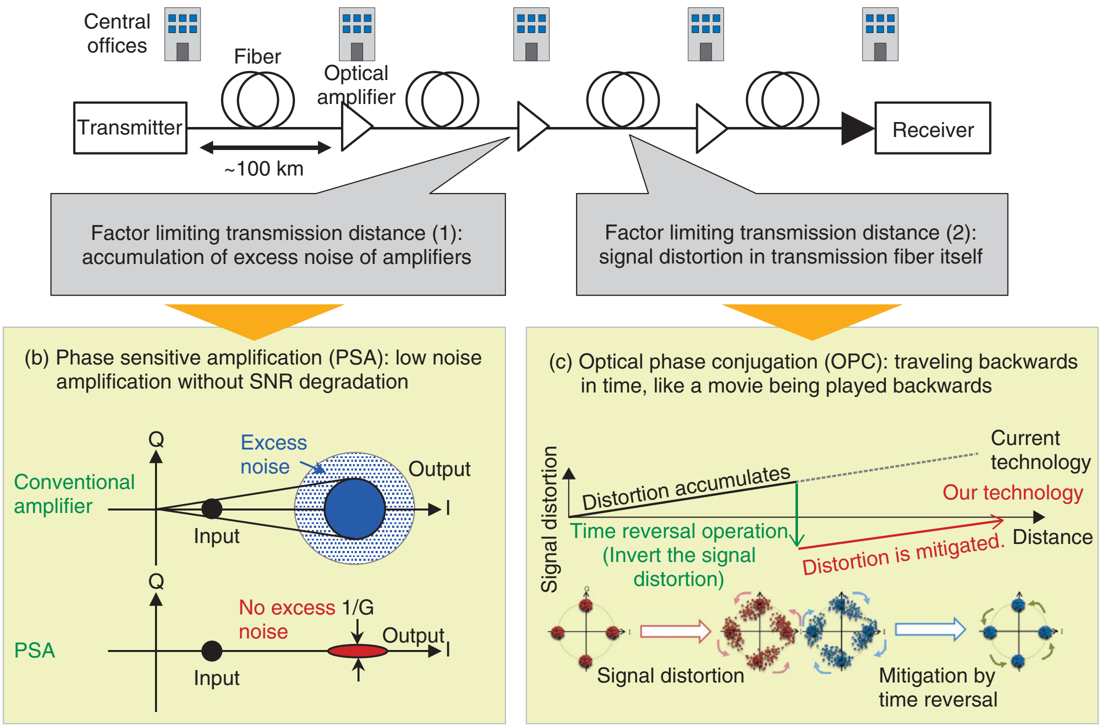
With conventional optical amplifiers such as the widely used erbium-doped fiber amplifier (EDFA), the noise figure cannot be reduced below the 3-dB quantum limit, which means that a multi-repeater transmission accumulates excess noise (**Fig. 1(b)**). Phase sensitive amplification (PSA), which has a phase-dependent amplification property, provides an ideal noise figure of 0 dB [2]. In other words, it makes optical amplification without SNR degradation possible (Fig. 1(b)).

Current digital coherent systems achieve long-haul transmission by using electrical digital signal processing in the transmitter/receiver to compensate for various types of signal waveform distortion that are present after signals are transmitted through optical fiber. In the future, as transmission capacity is further increased, signal waveform distortion in optical fiber (nonlinear impairment) will become apparent and will limit the extension of the transmission distance (**Fig. 1(c)**).

Optical phase conjugation (OPC)[*1] has the potential

[*1] OPC: Light has the same sort of wave-like properties as radio waves, and the timing of a wave's vibrations is called its phase. A wave in which the positive and negative phases have been reversed is called a phase conjugate wave, and the process of phase reversal is called optical phase conjugation. A phase conjugate wave is transmitted just as if it were traveling backwards in time, like a movie being played backwards, and is therefore sometimes called a time reversal wave.

(a) Factors limiting transmission distance



(d) Key device: PPLN

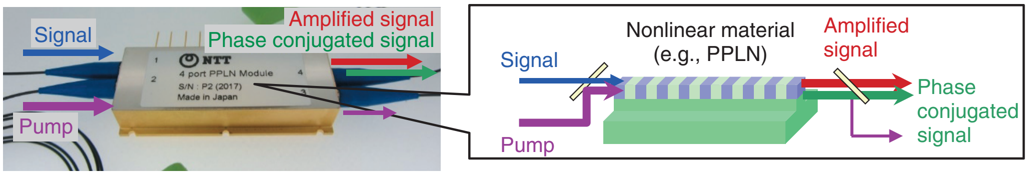


Fig. 1. Optical parametric amplification technology based on periodically poled lithium niobate (PPLN) waveguides.

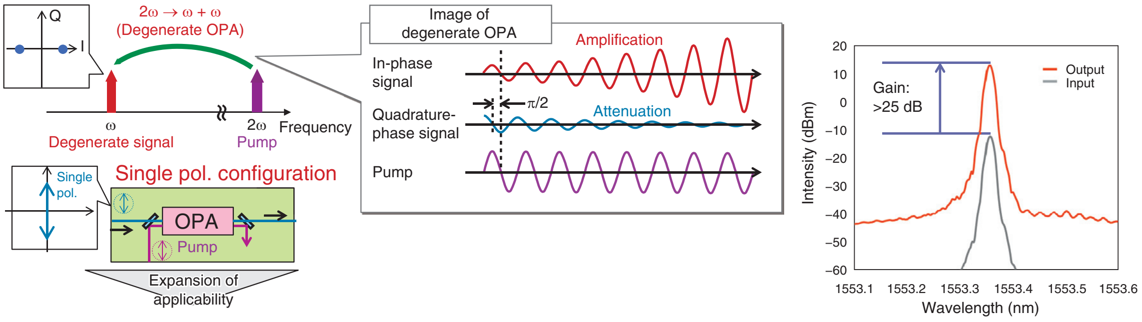
to mitigate the waveform distortion that occurs during optical fiber transmission by generating a time reversal wave. This technique can be likened to playing a movie backwards. If OPC is performed at a point in the middle of the optical fiber transmission path, the signal distortion that occurred in the first half of the transmission path can be compensated for in the second half. This makes it possible to improve the SNR by increasing the power of the optical signals. It also offers the possibility of simultaneously processing wavelength division multiplexed channels with a single optical phase conjugator. This is expected to greatly reduce both the amount of digital signal processing needed for distortion compensation and the electrical power consumption.

The PSA/OPC is achieved by optical parametric amplification (OPA), which transfers the energy of an intense pump to the signal (**Fig. 1(d)**). PSA/OPC can be implemented by inputting the signal and the pump, which is approximately twice the frequency of the signal light, into a nonlinear optical medium while appropriately adjusting the wavelength assignments and the phase relation of the signal light and pump light.

Our research group has developed PPLN[*2] as a nonlinear optical medium. We have developed a ridge-shaped waveguide structure that is highly resistant to photorefractive damage [3], and high-precision waveguide fabrication technology [4], which enables us to both utilize a high-power pump and

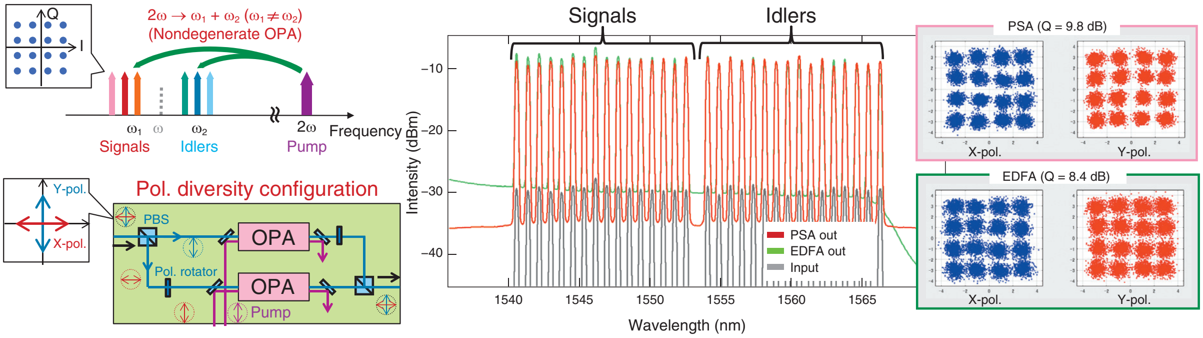
(a) Single channel, single pol., binary signal

(b) Gain of our PPLN module



(c) WDM, PDM, QAM signal

(d) Experimental result for PSA of PDM- and WDM-16QAM signals using both nondegenerate parametric amplification and the polarization diversity configuration



PBS: polarization beam splitter
PDM: polarization division multiplexing
Pol.: polarization
QAM: quadrature amplitude modulation
WDM: wavelength division multiplexing

Fig. 2. Increased gain and expanded applicability of phase sensitive amplifier.

achieve high conversion efficiency. We have also developed a fiber-pigtailed module that integrates a PPLN waveguide and couplers that split/multiplex pump light and signal light that have widely different wavelengths and thus achieve fiber input and output easily and stably (Fig. 1(d)). The module has four input/output fibers suitable for the respective wavelengths of the signal and pump light beams, and dielectric multilayer mirrors for multiplexing or splitting the signal and pump light beams. This structure achieves both high stability and low-loss optical coupling between the optical fiber and a PPLN waveguide.

3. Increased gain and expanded applicability of phase sensitive amplifier

In the OPA process, energy is transferred from a pump with a frequency of 2ω to a signal with a frequency of ω_1 and an idler with a frequency of ω_2. If $\omega_1 = \omega_2$, the process is called *degenerate OPA*, and a PSA can be obtained with gain for the in-phase component and attenuation for the quadrature phase component with reference to the pump phase (**Fig. 2(a)**). At the start of this research, the gain of a PPLN module was around 6 dB (quadruple). Now, having improved the efficiency of the PPLN waveguide and greatly reduced the coupling loss of the module, we can achieve a gain exceeding 25 dB (a 320-fold increase) (**Fig. 2(b)**), which can sufficiently

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*2 PPLN: Lithium niobate ($LiNbO_3$) is a crystalline material that exhibits nonlinear optical effects that enable light waves of different wavelengths to interact with each other. PPLN is an artificial crystal in which the orientation of positive and negative charges in the crystal is forcibly inverted with a fixed period inside the crystal by spontaneous polarization. With PPLN, it is possible to achieve an overwhelmingly high nonlinear optical effect compared with the original lithium niobate crystal.

compensate for the loss in the fiber transmission span.

It is also extremely important to ensure compatibility with the wavelength division multiplexing (WDM) and digital coherent technology used in existing optical communications systems. We have not only improved the performance of PPLN devices but also expanded the applicability of PSA because the above-mentioned degenerate OPA was only able to handle a binary modulation signal and a single wavelength. In addition, it could only amplify a single polarized wave since a second-order nonlinear optical medium such as PPLN is usually polarization dependent (Fig. 2(a)).

We have achieved the amplification of a quadrature amplitude modulation (QAM) signal and the simultaneous amplification of WDM signals (**Fig. 2(c)**) using nondegenerate OPA ($\omega_1 \neq \omega_2$) in a parametric process. We have also achieved PSA of a polarization division multiplexing (PDM) signal by using a polarization diversity configuration. In this configuration, the input signal is split with a polarization beam splitter (PBS), independently amplified with two OPA devices, and recombined using a PBS.

An experimental result for PSA of PDM- and WDM-16QAM signals using both nondegenerate parametric amplification and the polarization diversity configuration is shown in **Fig. 2(d)** [5]. We placed 16 carrier waves at intervals of 100 GHz at the transmitter and generated 20-Gbaud PDM-16QAM signals with pairs of phase-conjugated light beams. An 80-km dispersion-compensated fiber was used as the transmission line. At the receiver, one of the WDM signals was extracted using an optical filter, received by a digital coherent receiver, and demodulated using off-line signal processing. As shown in the input and output optical spectra in Fig. 2(d), all 16 WDM signals were simultaneously amplified with a gain of over 20 dB.

This figure shows the output spectrum of an EDFA with the same gain for comparison with the PSA. This comparison indicates that the optical SNR (OSNR) of the PSA was about 5 dB higher than that of the EDFA. The constellations of the PSA and the EDFA that were received and demodulated by a coherent receiver are also shown in Fig. 2(d). Distinct symbol separation with the demodulated signal for the PSA was clearly obtained as a result of low-noise amplification with a difference in signal quality (Q factor) of about 1 dB, which corresponded to the difference in OSNR.

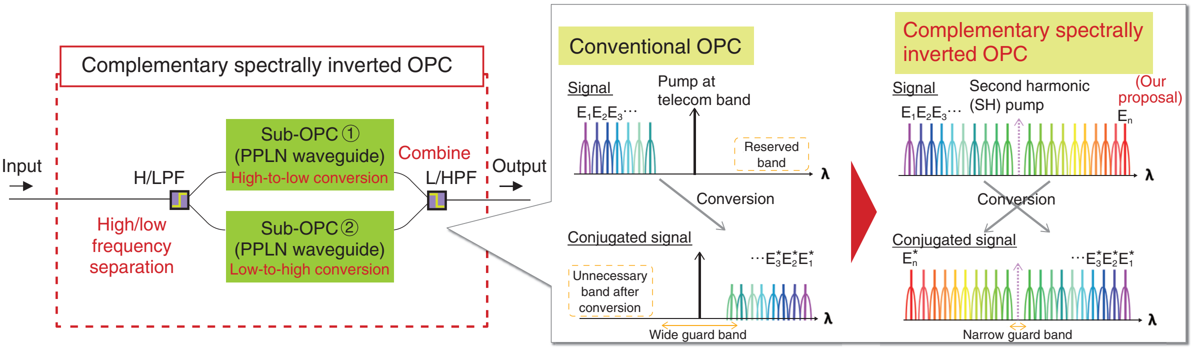
4. Proposal for complementary spectral inversion OPC and mitigation of nonlinear impairments

Digital signal processing can compensate not only for linear signal distortion but also for a nonlinear signal. However, further enhancement of the compensation performance requires an increase in the size of the signal processing circuit, which results in an increase in power consumption. OPC has long been studied with the aim of compensating for signal distortion in the optical domain without electrical signal processing. It was difficult to implement this approach with a high-capacity optical transmission system because conventional OPC occupies twice the bandwidth due to wavelength conversion, thereby reducing the spectral efficiency to less than half. To overcome this problem, we have developed a new optical signal processing circuit that spatially separates WDM signals into long-wavelength and short-wavelength signal channel groups and then applies OPC to each group using high-efficiency PPLN waveguide devices (**Fig. 3(a)**). Thus, we have achieved complementary spectrally inverted OPC that simultaneously compensates for the signal distortions of WDM signals without sacrificing the spectral efficiency.

An experimental result for the simultaneous phase conjugation of WDM signals is shown in **Fig. 3(b)**. We used 22.5-GBaud polarization multiplexed 16QAM signals with 92 WDM channels with a 25-GHz spacing. The optical spectrum at the transmitter and that after transmission over 3840 km (12 times recirculating loop transmission through a 320-km line) are also shown in Fig. 3(b). A comparison of the optical spectra indicates that the original signal bandwidth was retained, although the short- and long-wavelength bands, each with 46 channels, were exchanged 12 times. In addition, guard-band-less conversion was achieved except for one channel in the middle between the short- and long-wavelength bands, which is the pump bandwidth. We then achieved the highest-level transmission experiment yet reported in terms of both capacity (13.6 Tbit/s) and spectral efficiency (5.84 bit/s/Hz) using OPC [6].

We also conducted a transmission experiment using 96-Gbaud polarization multiplexed 8QAM signals in order to verify the applicability of this system to signals of 400 Gbit/s per channel. The transmission distances with and without OPC for respective optimal input powers of +6 dBm and +2 dBm are compared in **Fig. 3(c)**. This means that the use of phase conjugation

(a) New optical signal processing circuit



(b) Experimental result for simultaneous phase conjugation of WDM signals

(c) Transmission distance with and without OPC

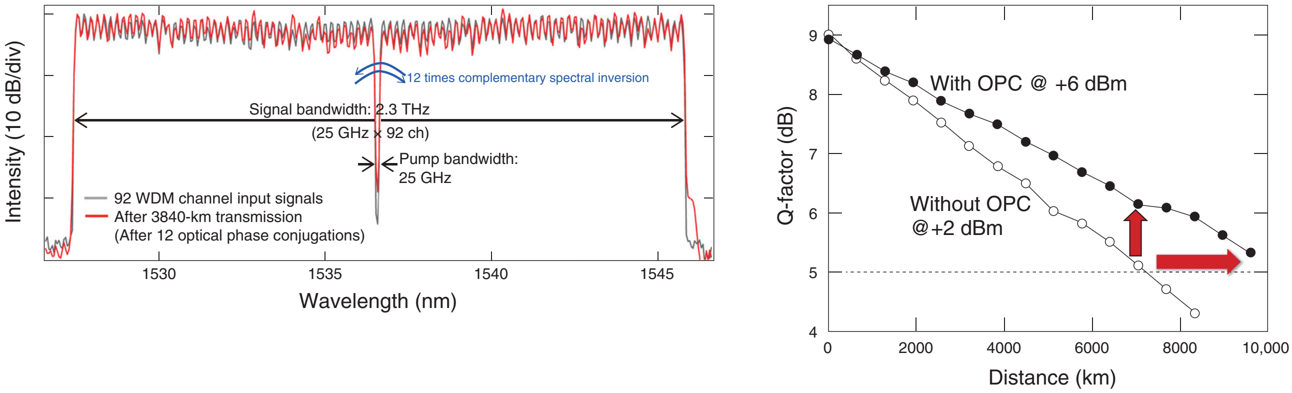


Fig. 3. Complementary spectrally inverted OPC.

enables *a higher power optical signal to be input into a transmission fiber*. Thus, it was demonstrated that the maximum transmission distance (when the forward error correction threshold value Q = 5 dB) can be extended from 7040 km to 9600 km. This was the first demonstration showing that the use of phase conjugation to compensate for signal distortion can be applied to an ultrahigh-speed baud signal at a level of 400 Gbit/s [7].

5. Future prospects

This article introduced the research and development (R&D) of OPA for optical communications with a view to improving the SNR in optical transport systems. This technology provides low-noise amplification and compensation for optical signal distortion and is also expected to lead to the generation/amplification of coherent light with various wavelengths using wavelength conversion techniques, and to quantum information processing such as squeezed light and photon pair generation. By further exploring this technology, we aim to create innovative technology that fully exploits optical coherence. Part of this research uses the results of “R&D on Optical Signal Transmission and Amplification with Frequency/Phase Precisely Controlled Carrier” commissioned by the National Institute of Information and Communications Technology of Japan.

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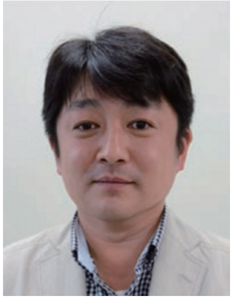

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Ultrahigh-speed Optical Front-end Device Technology for Beyond-100-GBaud Optical Transmission Systems

Munehiko Nagatani, Hitoshi Wakita, Yoshihiro Ogiso, Hiroshi Yamazaki, Minoru Ida, and Hideyuki Nosaka

Abstract

To support sustainable progress of optical communications, intense research and development (R&D) is being conducted to expand the transmission capacity per channel (transmission capacity per wavelength). Beyond-100-GBaud high-symbol-rate optical transmission technology is now attracting a great deal of attention for its use in constructing future cost-effective optical transport networks. This article introduces recent trends and challenges in optical communications and presents NTT's recent R&D in ultrahigh-speed optical front-end device technology for beyond-100-GBaud systems.

Keywords: high-symbol-rate optical transmission, bandwidth doubler, optical front-end device

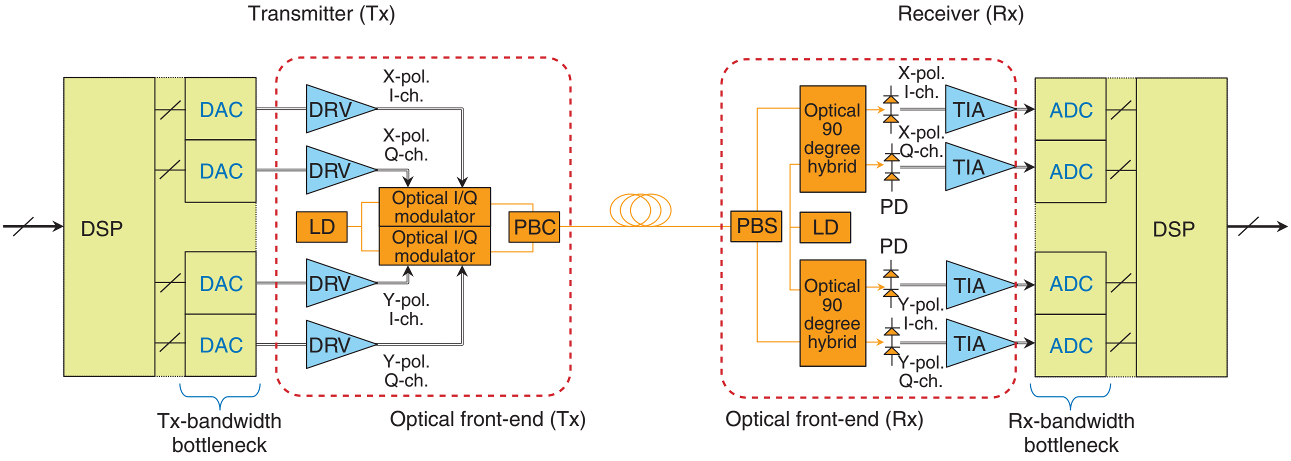
1. Trends and challenges in optical communications

The amount of data traffic in optical communications networks continues to grow exponentially due to the spread of broadband applications and services such as video streaming, cloud computing, and IoT (Internet of Things). In particular huge-capacity and long-haul transmission technology is required in the core network in order to accommodate client data and to link metropolitan areas. Novel digital coherent technology, which combines coherent detection and digital signal processing, has been deployed to cope with such rapid growth in communications traffic [1]. To date, 100-Gbit/s-per-channel (wavelength) systems based on 32-GBaud polarization division multiplexing (PDM) quadrature phase-shift keying and 400-Gbit/s-per-channel systems based on two-subcarrier 32-GBaud PDM 16-ary quadrature amplitude modulation (16QAM) have been put into practical use.

In the future, transmission capacity per channel is expected to exceed 1 Tbit/s to handle the ever-growing communications traffic. The transmission capacity can be increased by increasing the symbol rate, increasing the modulation order, or adding more subcarriers. Increasing the symbol rate is the most advantageous approach from the viewpoint of ensuring both cost effectiveness and transmission distance. Therefore, high-symbol-rate beyond-100-GBaud optical transmission technology is now attracting a great deal of attention for its use in constructing future optical transport systems with capacities exceeding 1 Tbit/s per channel.

Researchers face several challenges in constructing an optical transceiver enabling beyond-100-GBaud systems. A block diagram of a conventional optical transceiver for digital coherent systems is shown in **Fig. 1**. To construct a 100-GBaud system, each building block in the transceiver needs to have at least a 50-GHz analog bandwidth, which is the Nyquist frequency of 100 GBaud. One of the biggest challenges is finding a way to overcome the analog-bandwidth limitation of digital-to-analog converters (DACs) and analog-to-digital converters (ADCs), which are fabricated using Si (silicon) complementary metal oxide semiconductor (CMOS) technology.

The analog-bandwidth performance of cutting-edge



ADC: analog-to-digital converter
Ch.: channel
DAC: digital-to-analog converter
DRV: optical modulator driver
DSP: digital signal processor
I/Q: in-phase and quadrature
LD: laser diode
PBC: polarization beam combiner
PBS: polarization beam splitter
PD: photodiode
Pol.: polarization
TIA: trans-impedance amplifier

Fig. 1. Block diagram of conventional optical transceiver for digital coherent systems.

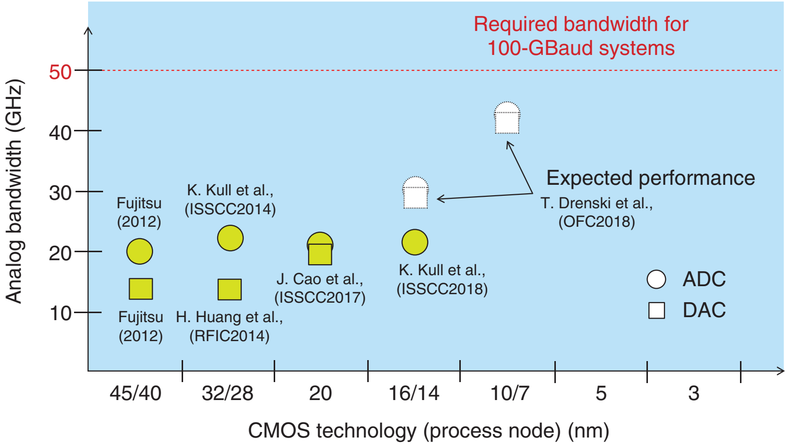
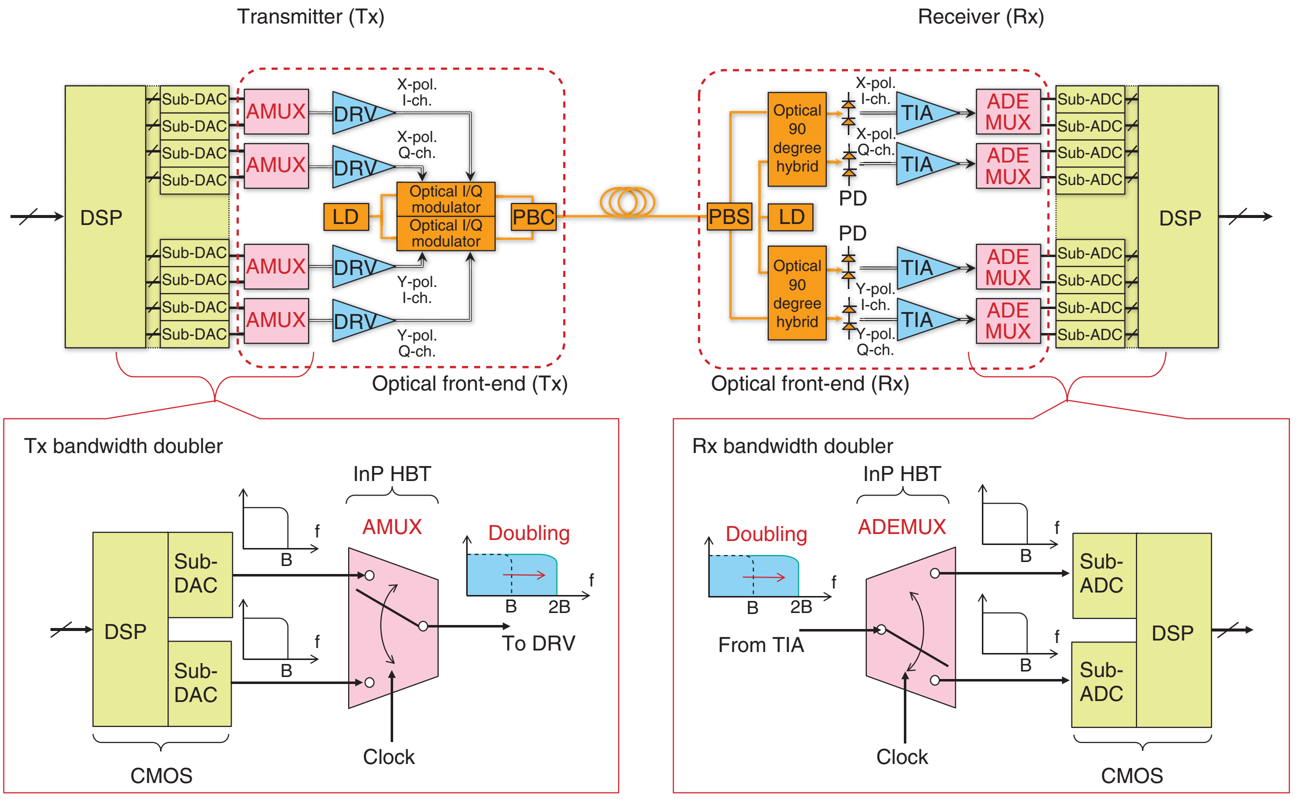


Fig. 2. Cutting-edge CMOS-based DACs and ADCs (analog bandwidth performance vs. CMOS technology).

CMOS-based DACs and ADCs is shown in **Fig. 2**. This graph indicates that it is very hard for CMOS-based DACs and ADCs to satisfy the target analog-bandwidth of over 50 GHz. One more unavoidable challenge is determining how to integrate and assemble optical front-end devices—modulator drivers (DRVs) and optical modulators on the transmitter side and trans-impedance amplifiers and photodiodes on the receiver side—into a packaged module to avoid a degradation in quality of beyond-100-GBaud signals due to extra loss derived from packaging. Hence, integration and packaging technology becomes much more important in beyond-100-GBaud systems.

2. Bandwidth doubler technology

We have devised novel bandwidth doubling technology to overcome the analog-bandwidth limitation of CMOS-based DACs and ADCs [2]. A block diagram of an optical transceiver applying the bandwidth doubler is shown in **Fig. 3**. On the transmitter



ADEMUX: analog demultiplexer
AMUX: analog multiplexer

InP HBT: indium phosphide heterojunction bipolar transistor

Fig. 3. Block diagram of optical transceiver applying bandwidth doubler technology.

side, two pre-processed analog signals from CMOS-sub-DACs are multiplexed into one double-bandwidth signal by the analog multiplexer (AMUX). On the receiver side, one broadband signal is demultiplexed into two half-bandwidth signals by the analog demultiplexer (ADEMUX), and they are digitized and post-processed by the following CMOS-sub-ADCs and digital signal processor. Using this bandwidth doubler technology, we can expand the usable baseband signal bandwidth twice and achieve twice the symbol rate compared with a conventional transceiver (which is why we call this technology bandwidth doubler).

The AMUX and ADEMUX integrated circuits (ICs) for the bandwidth doubler were designed and fabricated using our in-house indium phosphide heterojunction bipolar transistor (InP HBT) [3]. We have already succeeded in conducting a proof-of-principle experiment and beyond-100-GBaud optical transmission [4]. In addition, we recently demonstrated the world's first 1-Tbit/s-per-channel long-haul WDM (wavelength division multiplexing) optical transmission using 120-GBaud probabilistically shaped PDM 64QAM [5]. These results confirmed that the bandwidth doubler is promising for future beyond-100-GBaud systems.

3. The latest AMUX IC and 160-GBaud signal generation

We are now developing faster AMUX and ADEMUX ICs to further improve optical transmission performance. Using newly developed in-house 0.25-μm InP HBT technology [6], we succeeded in developing an AMUX IC with a bandwidth over 110 GHz (a world record) in 2018 [7]. The performance of the 0.25-μm InP HBTs and AMUX IC is summarized in **Fig. 4**. The fabricated HBTs have a peak f_T (cutoff frequency) and f_{max} (maximum oscillation frequency) of 460 and 480 GHz, respectively. The AMUX IC consists of two input buffers, a clock buffer, an AMUX core, and an output buffer. It is designed to

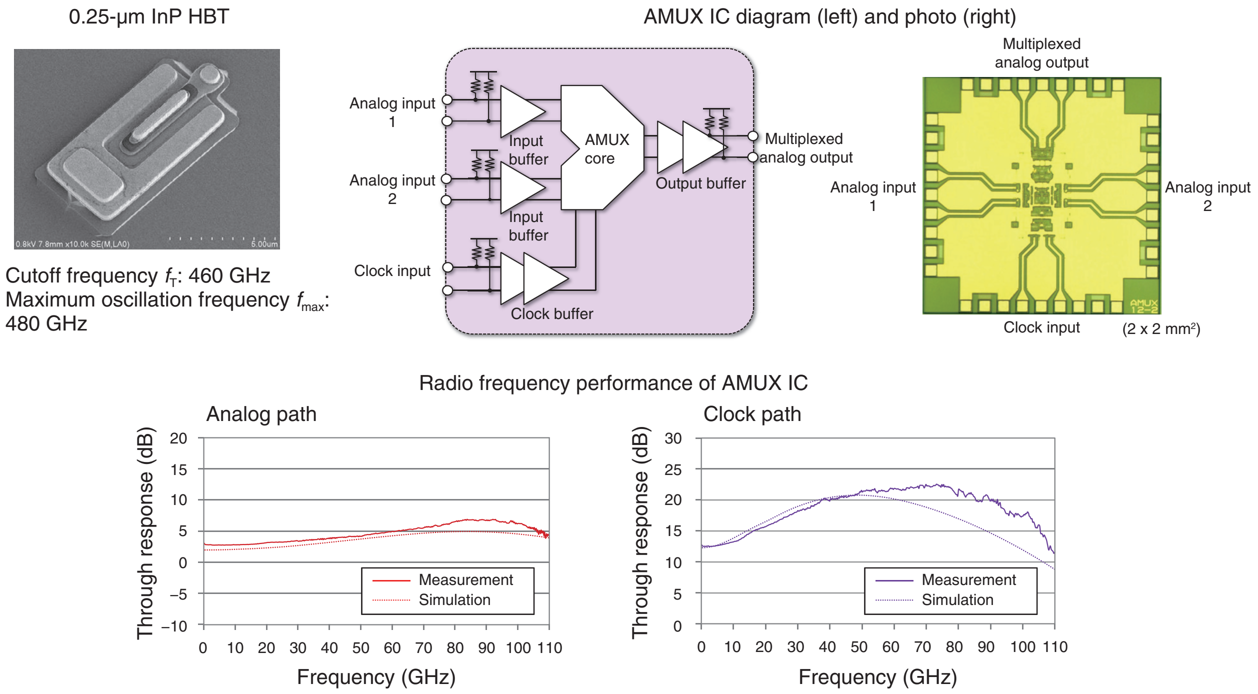


Fig. 4. Images of 0.25-μm InP HBT and AMUX IC and radio frequency performance of AMUX IC.

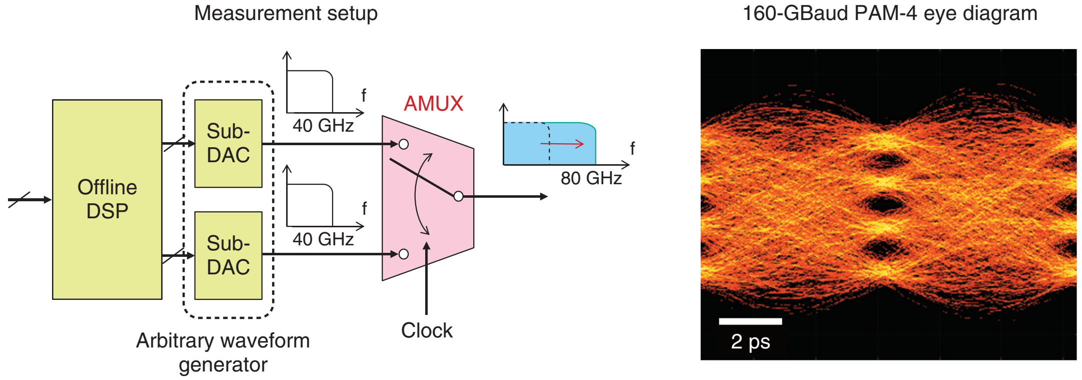


Fig. 5. Demonstration of 160-GBaud PAM-4 (4-level pulse amplitude modulation) signal generation.

have broad peaking characteristics in its frequency response to compensate for packaging loss.

The measured bandwidths for the analog and clock paths were both over 110 GHz. These measurement results indicate that this AMUX IC can potentially be used in constructing a 110-GHz-bandwidth 220-GS/s DAC subsystem and to generate 200-GBaud-class modulated signals. We have already demonstrated signal generation at ultrahigh symbol rates by applying this AMUX IC to the bandwidth doubler. The measurement setup and results are shown in **Fig. 5**. In this demonstration, we succeeded in generating a 160-GBaud PAM-4 (4-level pulse amplitude modulation) signal with two 40-GHz-bandwidth sub-DACs and the AMUX IC and demonstrating the further scalability of the bandwidth doubler technology [8]. Digital coherent optical transmission with a capacity of over 1-Tbit/s per channel will be achievable by using this AMUX IC.

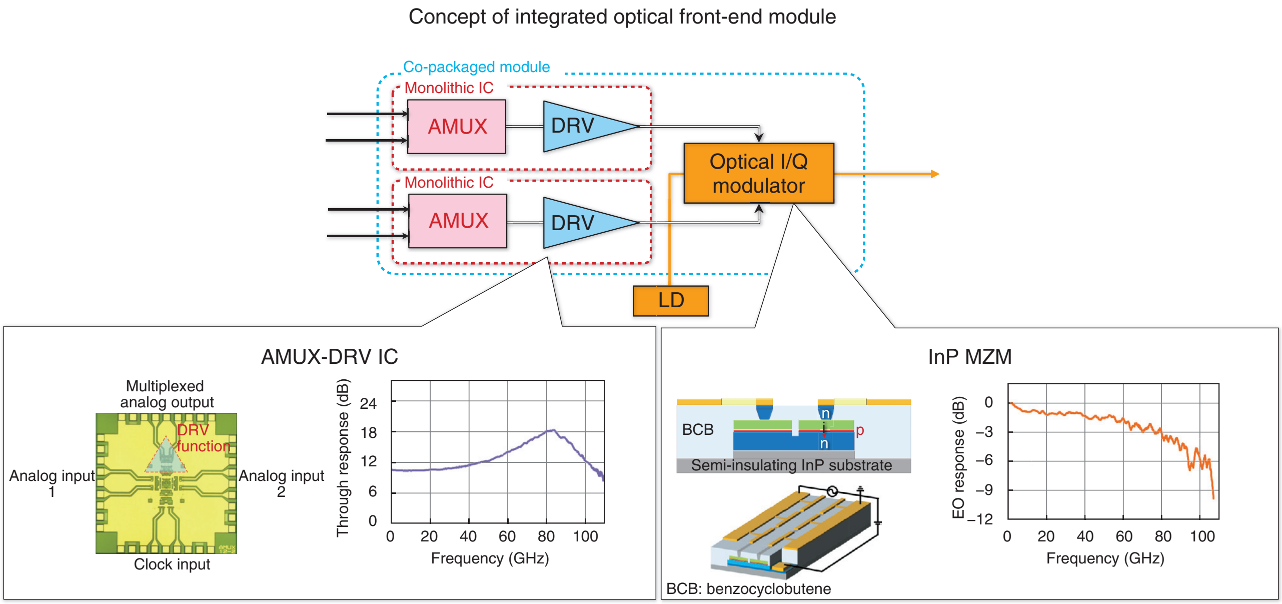


Fig. 6. Conceptual block diagram of integrated optical front-end module and performance summary of AMUX-DRV IC and InP MZM.

4. Concept of ultrahigh-speed integrated optical front-end module

One more important issue for beyond-100-GBaud systems is integration and packaging technology, as mentioned in the first section. This is especially true regarding the transmitter, where the AMUXs, DRVs, and optical modulators have to be placed as close to each other as possible. In addition, all these devices have to be assembled into one integrated packaged module in order to ensure the quality of ultrabroadband modulated signals.

We have developed an AMUX IC equipped with a DRV function (AMUX-DRV IC) and studied a design incorporating the AMUX-DRV IC and optical modulators for an ultrahigh-speed integrated optical front-end module. Because monolithic integration of the AMUX function and DRV function into one chip is advantageous for ensuring the signal quality and reducing power consumption, we replaced an output buffer with a DRV function block consisting of a high-gain, high-linearity, and large-output-swing amplifier in the AMUX IC, and designed the AMUX-DRV IC. For the optical front-end, we used in-house InP MZM (Mach-Zehnder modulator)-based optical IQ (in-phase and quadrature) modulators, which have an electro-optical (EO) modulation bandwidth of 80 GHz. The AMUX-DRV IC was designed to have broad peaking characteristics to compensate for the frequency response of the following modulator and to have optimum output impedance and driving voltage for the modulator.

A conceptual block diagram of the integrated optical front-end module is shown in **Fig. 6**, which also summarizes the performance of the AMUX-DRV IC and InP MZM. The AMUX-DRV IC has broad peaking characteristics and ultrabroad bandwidth of over 110 GHz as expected. With this AMUX-DRV IC, the optical front-end module could be expected to have an ultrabroad EO bandwidth of 80 GHz. We have actually already fabricated a sub-assembly that contains the AMUX-DRV IC and InP MZM and have succeeded in demonstrating 400-Gbit/s-per-channel DMT (discrete multi-tone) signal optical transmission [9]. This is a record for IMDD (intensity modulation and direct detection) optical transmission so far and indicates the capability of over-1-Tbit/s-per-channel digital coherent optical transmission. In the next step, we will complete the optical front-end module and apply it to digital coherent optical transmission.

5. Summary

In this article, we introduced recent trends and challenges in optical communications and our research and development (R&D) of ultrahigh-speed optical front-end device technology for future beyond-100-GBaud systems. We will continue to promote further speed improvements and continue with our R&D so that this technology can ensure sustainable progress of optical communications.

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Toward Terabit-class Wireless Transmission: OAM Multiplexing Technology

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Takayuki Yamada, Takana Kaho, and Hiroshi Hamada

Abstract

NTT is researching and developing technology with the aim of achieving terabit-class wireless transmission that achieves the next generation of 5G (fifth generation). In particular, we are investigating orbital angular momentum (OAM) multiplexing transmission technology utilizing the OAM of electromagnetic waves as a new spatial multiplexing technology capable of transmitting multiple radio waves at the same time using the same frequency band. In an experiment on OAM multiplexing transmission using the 28-GHz band, we successfully demonstrated the world's first 120-Gbit/s wireless transmission. This article introduces the details of this technology.

Keywords: high-capacity wireless transmission technology, OAM multiplexing, OAM-MIMO multiplexing

1. Introduction

The coming 5G (fifth generation) will accelerate the use of wireless communications in all fields including connected cars, virtual reality/augmented reality, and high-definition video transmission. Mobile traffic is expected to increase by 1.5 times annually, and from such a trend, it is expected that wireless transmission at the hundreds-of-gigabits to the terabit class will be necessary in the 2030s.

To provide for the ever-increasing demand for wireless communications, NTT is researching and developing technology with the aim of achieving terabit-class wireless transmission. There are three directions that can be taken to increase capacity in wireless communications: increasing the spatial multiplexing[*1] order, broadening the transmission bandwidth, and increasing the modulation level (**Fig. 1**).

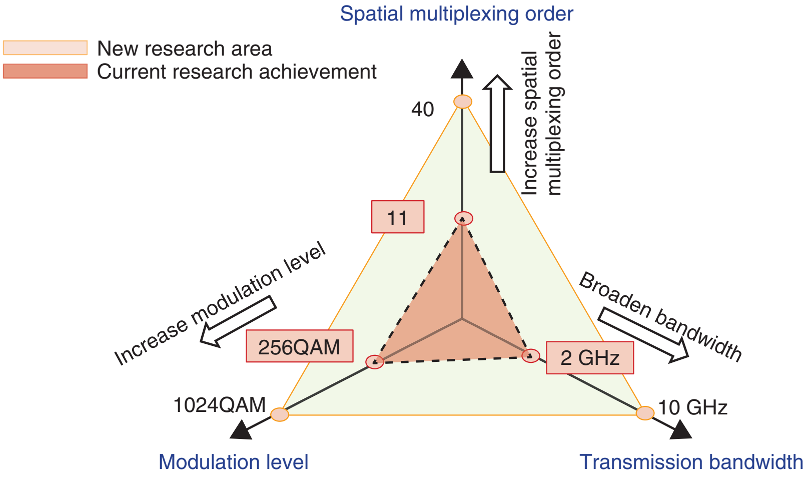
Of these, the direction involving increasing the modulation level is already reaching the limit. For example, to obtain twice the capacity of 1024QAM (quadrature amplitude modulation), which transmits 10 bits of information at a time, it is necessary to carry out one million QAM modulation to transmit 20 bits of information at a time. Consequently, it is difficult to achieve large capacity with this approach.

NTT is taking the approach of broadening the transmission bandwidth using the quasi-millimeter wave[*2] band and increasing the spatial multiplexing order through the use of a new principle based on electromagnetic waves having orbital angular momentum (OAM)[*3].

[*1] Spatial multiplexing: A signal multiplexing method that sends and receives multiple data streams in parallel by using multiple spatially independent electromagnetic waves.

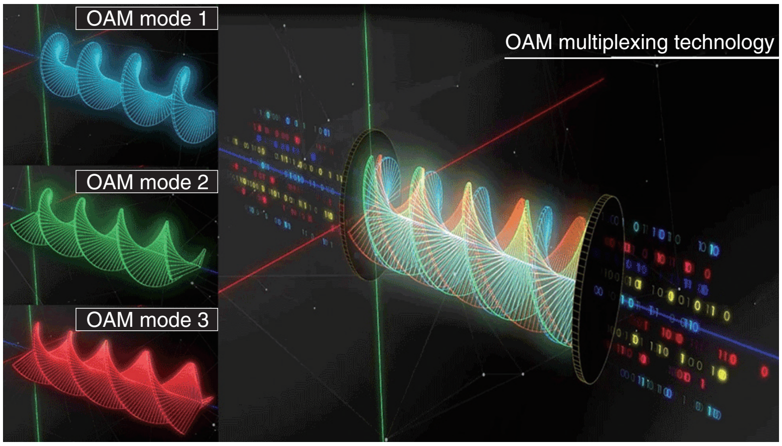
[*2] Millimeter waves, quasi-millimeter waves: Millimeter waves refer to the radio waves with a wavelength of 1–10 mm, in the frequency band of 30–300 GHz and that feature strong rectilinear propagation similar to that of microwaves. Quasi-millimeter waves refer to radio waves with a wavelength that, at 1–3 cm, are close to those of millimeter waves in the frequency band of 10–30 GHz.

[*3] OAM: The nature of radio waves is such that the angular momentum of radio waves is represented by the product of position coordinates and the conjugate momentum; radio waves with different OAM are not correlated, so they can be separated independently even if they overlap.



QAM: quadrature amplitude modulation

Fig. 1. Research directions toward large-capacity wireless transmission.



(a) Trace of the same phase (b) Concurrent transmission

Fig. 2. Principle of OAM multiplexing transmission technology.

2. Principles of OAM multiplexing transmission and NTT's new transmission technology

In this section, we explain OAM multiplexing transmission and introduce a new wireless transmission technology developed by NTT.

2.1 OAM multiplexing transmission

OAM multiplexing transmission is a technique to increase the number (multiplexing number) of data signals to be transmitted at the same time by transmitting different signals using radio waves having different OAM modes [1, 2]. OAM is a property of electromagnetic waves expressing phase rotation on the vertical plane in the propagation direction. The number of phase rotations is called an OAM mode. When an electromagnetic wave has this OAM property, the trace of the same phase takes on a helical shape in the direction of propagation (**Fig. 2**). For example, the trace of the same phase in OAM mode 1, OAM mode 2, and OAM mode 3 is shown in Fig. 2(a).

Radio waves having this OAM property cannot be

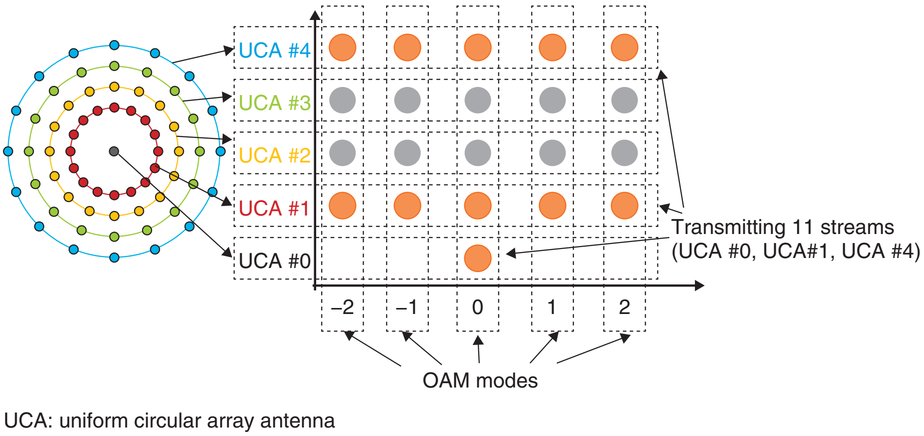


Fig. 3. Example of configuring OAM-MIMO multiplexing transmission.

received without a receiver having the same number of phase rotations at the time of transmission. For this reason, if multiple radio waves having different OAM modes are superposed, they can eventually be separated without mutual interference as long as there is a receiver that can receive radio beams with the same phase rotations corresponding to each OAM mode. For instance, an example is shown in Fig. 2(b) where different signals are put on OAM modes 1, 2, and 3 and transmitted simultaneously. Technology for transmitting multiple data signals using this feature is called OAM multiplexing transmission technology.

Research on radio wave OAM dates back to the beginning of the 20th century. More recently, with the maturing of large-capacity transmission technologies using high-frequency bands in the 2010s, OAM multiplexing transmission in the millimeter-wave band has been attracting attention. An example of a recent achievement is a demonstration at the University of Southern California in the United States of 32-Gbit/s transmission using the 28-GHz band in 2014 and the 60-GHz band in 2016 [3, 4].

2.2 OAM-MIMO (multiple-input multiple-output) wireless multiplexing transmission technology

In theory, the OAM mode order (number of phase rotations) can be infinitely increased, so the spatial multiplexing order can be infinitely increased by OAM multiplexing transmission. However, radio waves with the property of OAM have the characteristic such that the electric energy diverges spatially as the propagation distance becomes larger as the OAM mode becomes higher. Thus, there is a practical limitation to the use of the higher order OAM modes to increase the spatial multiplexing order.

NTT has devised OAM-MIMO multiplexing transmission technology that integrates the widely used MIMO[*4] technology in order to efficiently increase the spatial multiplexing order while overcoming the practical limitation [5]. The devised OAM-MIMO multiplexing transmission technology allows the usage of the same OAM modes. In particular, multiple sets of low OAM mode signals are simultaneously transmitted to address the divergence issue of higher OAM modes. The nature of OAM multiplexing that generates multiple independent channels among different OAM modes is still applicable.

At the same time, the MIMO concept is exploited to increase the number of concurrently transmitted data streams. By properly exploiting MIMO technology, it is possible to separate signals between multiple sets of the same OAM modes while maintaining noninterfering properties between different OAM modes.

A configuration example of OAM-MIMO multiplexing transmission technology is illustrated in **Fig. 3**. This figure shows an example in which a total of 11 multiplexing transmissions to be described later are performed. The left figure represents four uniform circular array antennas (UCAs) concentric with one in the center. UCAs #1 to 4 can generate OAM modes –2, –1, 0, 1, and 2, respectively, and five OAM modes

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[*4] MIMO: Radio signal processing technology for improving the quality of communications by using multiple antennas at both the transmitter and receiver. It has attracted the attention of the wireless communications industry since it can greatly improve throughput and transmission distance without having to increase bandwidth or power.

can be generated and transmitted. The antenna in the center (described as UCA #0 for notation convenience) is used for the axis alignment and/or transmission of OAM mode 0. The signals multiplexed in the same mode are separated by MIMO technology at the receiver.

3. World-first transmission of over 100 Gbit/s using 28-GHz band

To demonstrate the effectiveness of the OAM-MIMO multiplexing transmission technology, NTT has developed a transmitter and receiver that uses a bandwidth of 2 GHz in the 28-GHz band (**Fig. 4**). The developed transmitter/receiver consists of four concentric UCAs with different radii and one antenna in the center. Each UCA is composed of 16 antenna elements and can transmit and receive radio waves in 5 OAM modes. Simultaneous transmission of a total of 21 data signals is possible using these antenna elements. Although frequency bands under 6 GHz have been used in the past, the development of equipment that can simultaneously transmit up to 21 signals in quasi-millimeter-wave and higher frequency bands is a world first.

The configuration of this transmitter/receiver and the experimental setup are shown in **Fig. 5**. On the transmitter side, signals are generated and converted into analog intermediate frequency (IF) band signals using arbitrary waveform generators that work as digital-to-analog converters. IF signals are inserted into the developed transmitter. The input signal is transmitted by each UCA via an OAM mode generation circuit after up-converting IF signals to the 28-GHz band. On the receiver side, the wireless signals received by each UCA are separated into each OAM mode by OAM mode separation circuits, and then separated signals are down-converted into IF band signals. Those IF band signals are converted to digital signals by the digital oscilloscope, which is used as an analog-to-digital converter. Finally, the digital signals are processed to extract each transmitted signal. Here, the OAM mode generation circuit and the OAM mode separation circuit were respectively achieved by designing a 5 × 16 and a 16 × 5 wideband Butler matrix circuit. Five OAM modes can be simultaneously generated and separated by the wideband Butler matrix circuits.

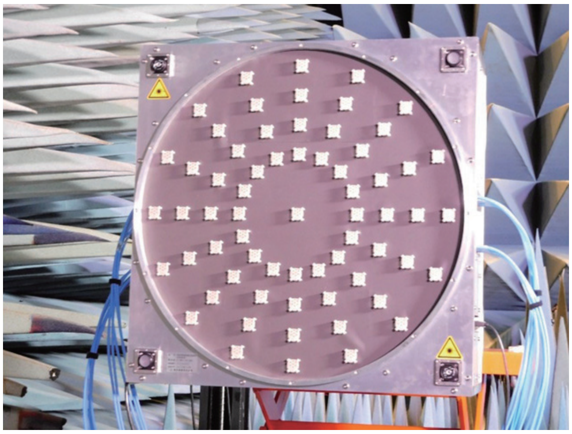

Fig. 4. Developed transceiver.

Using this transmitter/receiver, we conducted a transmission experiment at a distance of 10 m in a shield room. Multiple data signals were wirelessly transmitted using multiple OAM multiplexed radio waves. We confirmed that wireless transmission was possible according to the OAM principle. In addition, we succeeded in the world-first large-capacity wireless transmission of 120 Gbit/s [6] by multiplexing 11 data signals of 9.6 to 13.3 Gbit/s. We also successfully implemented the corresponding signal processing technology that can handle such multiplexed signal transmission and reception.

4. Expectation for broadband technology

Technology to utilize wide frequency bands is currently being studied. For example, the mixer integrated circuit (IC) and module in the 300-GHz band shown in **Fig. 6** make it possible to both expand the transmission bandwidth and improve the signal-to-noise ratio, which had been a problem in the conventional 300-GHz band radio front end [7]. We used this device to carry out 100-Gbit/s transmission in one stream using a wide bandwidth of 25 GHz. By combining such wideband IC technology and OAM multiplexing transmission technology, we can expect to achieve even larger capacity.

5. Future work

In order to use OAM multiplexing technology in a real environment, it is necessary to address practical issues that occur in the real environment and to conduct experimental evaluations in various environments. We are now preparing to verify the feasibility of OAM multiplexing in the field by conducting outdoor wireless transmission experiments. In addition, we will utilize frequency bands that can use wider

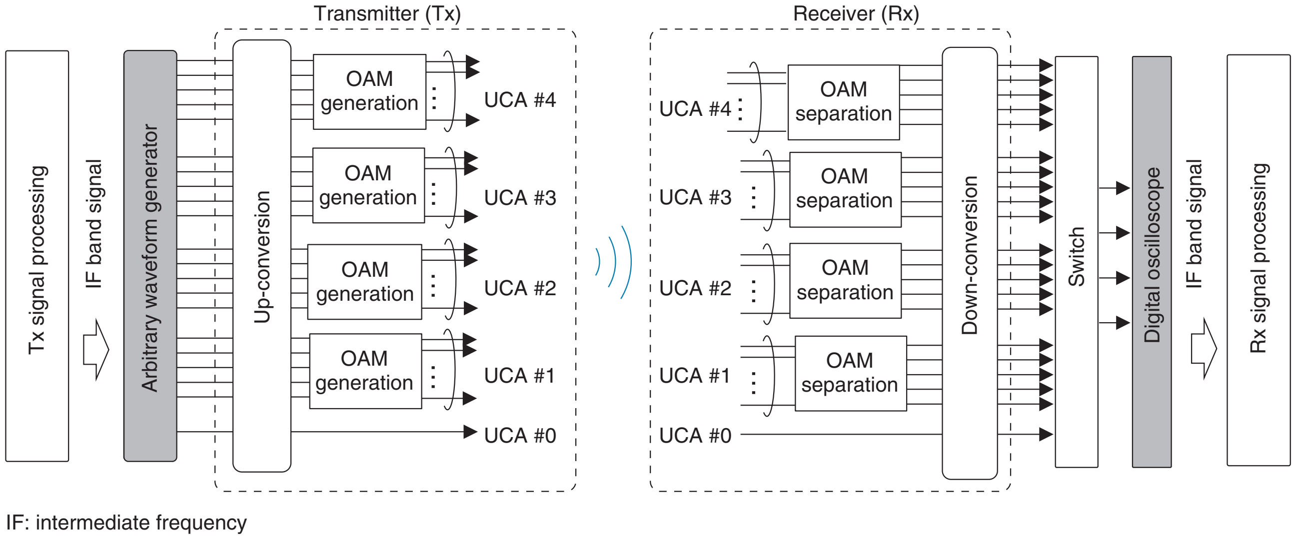

Fig. 5. Configuration of transmitter and receiver.

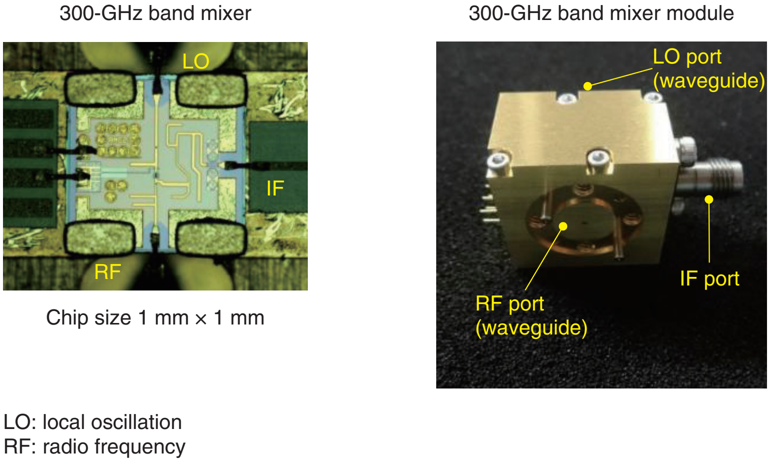

Fig. 6. 300-GHz band mixer and IC module.

bandwidths and lead research and development toward realizing terabit-class wireless communications.

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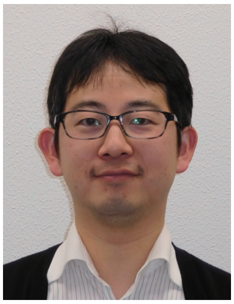

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Recent Progress in Applications of Optical Multimode Devices Using Planar Lightwave Circuits

Junji Sakamoto and Toshikazu Hashimoto

Abstract

The optical propagation mode—the electromagnetic field distribution of light propagating through a waveguide—is attracting attention as a new degree of freedom of light and is expected to provide new functions and improved optical characteristics in optical devices and systems. In this article, we introduce optical device technologies that utilize the optical propagation mode in an integrated optical waveguide component called a planar lightwave circuit.

Keywords: multimode, waveguide, PLC

1. Introduction

In optical communications, the degrees of freedom of light such as its intensity, wavelength, phase, and polarization have been used for multiplexing and higher-order modulation [1]. In an optical waveguide, the optical field propagates in specific distribution patterns called modes. Single-mode transmission with only the fundamental mode has mainly been used in optical communications. In recent years, however, large-capacity transmission using mode multiplexing has been reported [2]. This is called spatial division multiplexing (SDM) because it uses the degree of freedom of the spatial optical field distribution.

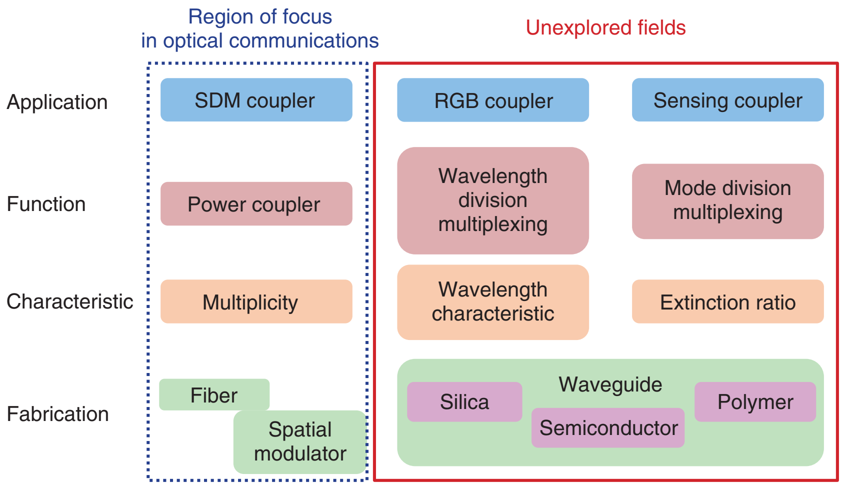
Optical propagation modes are also expected to be utilized for the next generation of technology for optical signal processing and sensing, as well as for SDM transmission. For stable optical performance, optical communications systems are generally composed of devices for single-mode transmission, which include a light source, modulator, and multiplexer. Therefore, an important component to handle the modes is a mode converter (MC) that can convert the fundamental mode and higher-order modes.

A technology map of MCs is shown in **Fig. 1**. There are MCs using optical fiber, spatial modulators such as liquid crystal on silicon, and waveguides. Since mode utilization has been limited to SDM transmission, the focus has mainly been on signal multiplexing. For other functions such as wavelength multiplexing and sensing, precise mode conversion is necessary.

We are now researching silica planar lightwave circuit (PLC) technology and various devices using it as a means of controlling modes. In this article, we introduce a wavelength division multiplexer using optical propagation modes and an ultralow-crosstalk MC for an optical time domain reflectometer (OTDR).

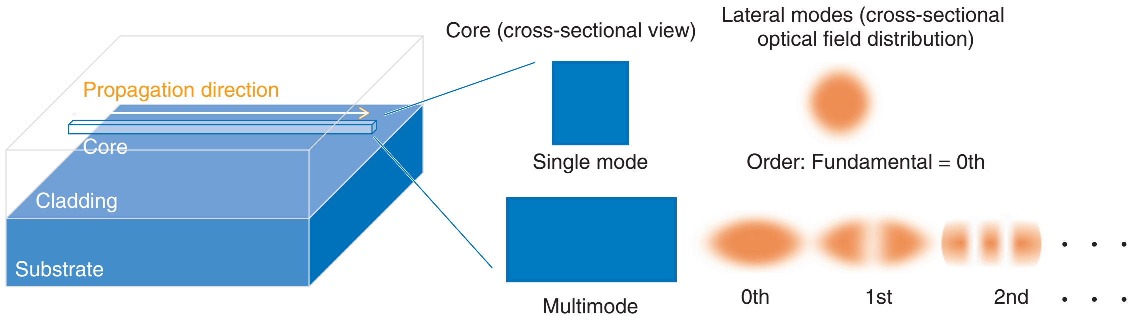
2. Structure of optical multimode waveguide

A PLC is a waveguide circuit composed of a silica core and cladding on a substrate such as Si (silicon) or SiO_2 (silicon dioxide), as shown in **Fig. 2(a)**. A waveguide pattern is fabricated using standard wafer processes such as photolithography and reactive ion etching. The core structure of single-mode and multimode waveguides is shown in **Fig. 2(b)**; the intensity of optical field distribution with several modes is also shown in a cross-sectional view. The core width and height of the single-mode waveguide enable only the fundamental mode to exist in a lateral direction. The



RGB: red, green, and blue color model

Fig. 1. Technology map of MCs.



(a) (b)

Fig. 2. (a) Structure of waveguide. (b) Cross-sectional view of cores and optical field distributions in single and multimode waveguides.

intensity of the optical field distribution is shown at the upper right of Fig. 2(b). A multimode waveguide has a core size in which first or higher-order modes can coexist with the fundamental mode. The number of modes that can exist is determined by the core size.

The intensity of optical field distribution is shown at the lower right of Fig. 2(b). In the waveguide, the mode should be precisely controlled for various applications by changing the width of the core, since the characteristics change when the modes propagating through the waveguide change. PLC technology could be the most promising approach for providing such highly accurate fabrication of waveguides, since it has been developed for application to optical communications for many years [3]. In the following sections, we introduce several applications using multimode PLC technology.

3. RGB coupler

A compact red (R)-green (G)-blue (B) multiplexer for laser diodes is attractive for use in glass-based displays, head-mounted displays, and compact projectors. Such laser imaging applications use multiple laser sources and multiplex them into a single beam that is then scanned onto a screen by a beam scanner such as a microelectromechanical system mirror. RGB multiplexers have conventionally been

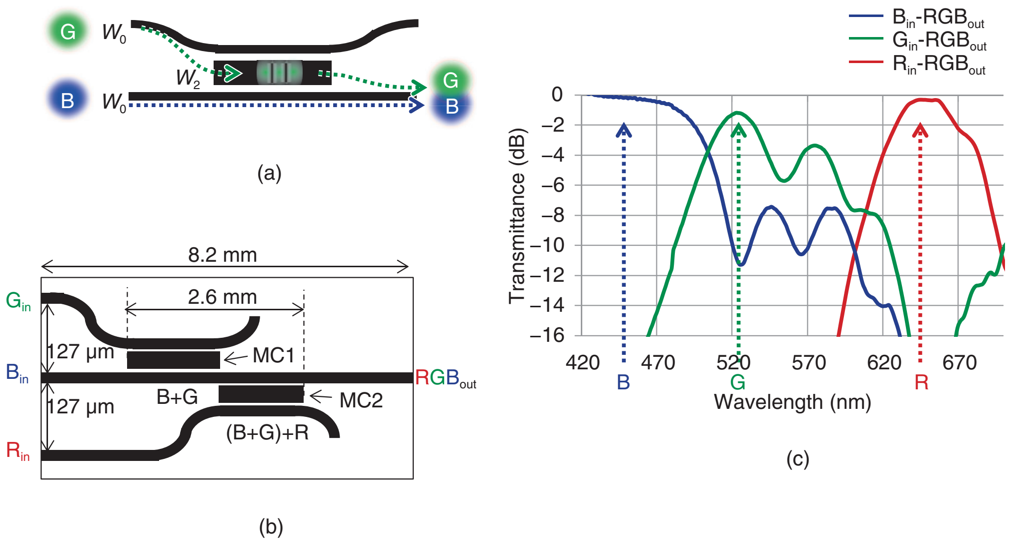


Fig. 3. (a) Wavelength multiplexer using MCs. (b) Optical circuit of the RGB coupler. (c) Spectra of the RGB coupler.

constructed by using mirror prisms, multilayer films, and optical fibers. An RGB multiplexer (RGB coupler) based on a PLC is promising for downsizing to a single chip integrating the functions used in a conventional RGB multiplexer [4, 5].

An RGB coupler typically uses directional couplers (DCs) to multiplex light with different wavelengths. The wavelength dependence of the coupling length is used to implement the wavelength multiplexing function because the higher the wavelength is, the shorter the coupling length becomes. For example, a DC structure is designed to match the coupling length of blue light and the recoupling length of green light. Then the blue and green lights are multiplexed by the DC. It is difficult to multiplex more than three wavelengths this way, and even in the case of two wavelengths, the DC tends to become long due to the need for period-matching between the coupling and recoupling.

To solve this problem, we developed an RGB coupler using MCs, each of which includes an additional multimode waveguide that is wider than the single-mode waveguides. The added multimode waveguide is sandwiched between the single-mode waveguides of a conventional DC, as shown in **Fig. 3(a)**, where the black line represents the core of the optical circuit. The additional multimode waveguide works as an MC that converts between 0th-order and higher-order modes. Because the MC converts only wavelengths satisfying the conversion conditions, it is possible to selectively multiplex desired wavelengths. For example, when the MC is designed to satisfy the conversion conditions at the green wavelength, the green light can move to the next single-mode waveguide by means of mode conversion.

In contrast, almost all the blue light goes through the MC, as shown in Fig. 3(a). Since this coupling structure can multiplex green and blue light as if it were wavelength-independent thanks to suppression of the transition of unwanted-wavelength light, the coupler length does not need to be the lowest common multiple of the coupling lengths of the colors. As a result, the coupler can be shorter than conventional DCs.

Our RGB coupler using MCs is shown in **Fig. 3(b)**. Because MC1 and MC2 were designed to satisfy the coupling conditions at the green and red wavelengths, the coupler can multiplex R, G, and B into the same waveguide. The total length of MC1 and MC2 is 2.6 mm, which is less than half as long as the conventional RGB coupler using DCs.

The measurement results for the RGB coupler fabricated using PLC technology is shown in **Fig. 3(c)**. The transmittances are −0.3 dB for blue, −1.2 dB for green, and −0.3 dB for red. Although the transmittance of green light is relatively low, the results confirmed that we succeeded in making a very small RGB coupler with low loss (better than 1.5 dB) using MCs.

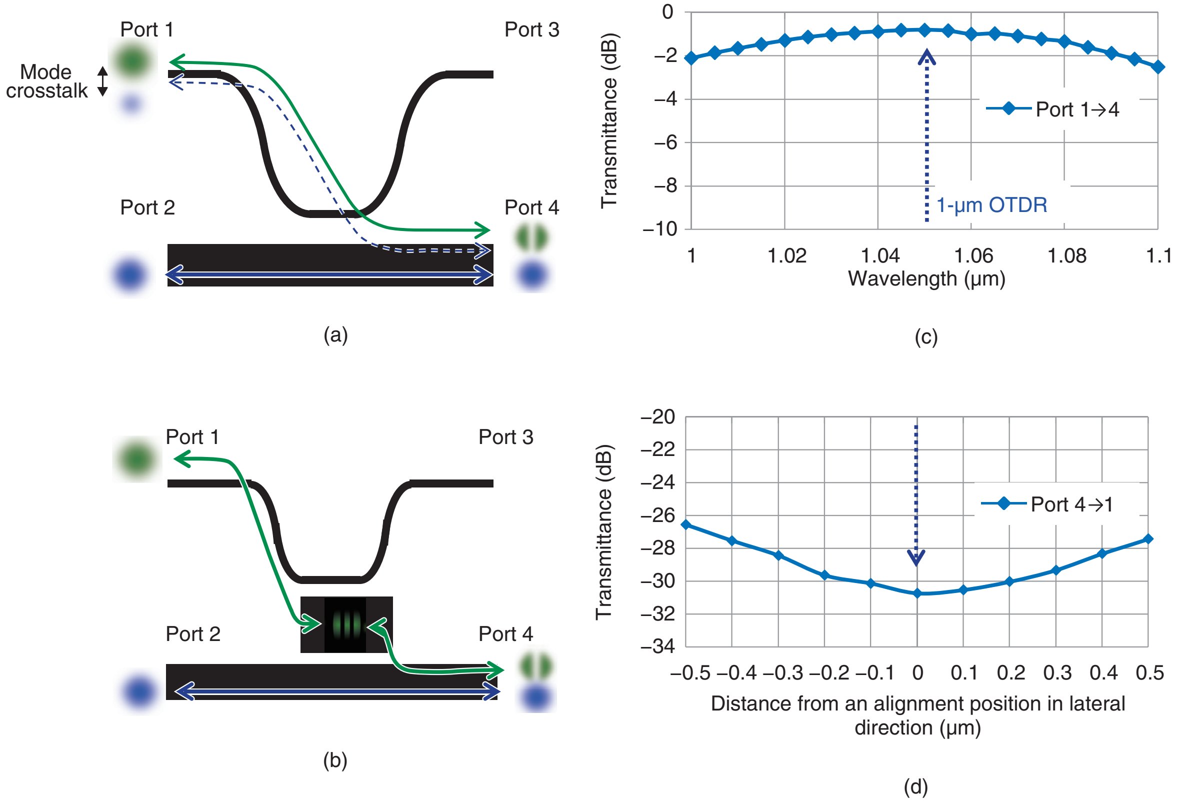


Fig. 4. (a) Conventional structure and operation of mode coupler. (b) Structure of mode coupler with low mode crosstalk. Measured (c) conversion efficiency and (d) mode crosstalk.

4. Sensing coupler for sensitive OTDR

An OTDR is used to diagnose optical fiber links. A 1-µm-band mode-detection OTDR (1-µm OTDR) system has been reported [6, 7] that uses 1-µm-band probe pulses to generate not only the fundamental mode but also the first-order mode as backscattered light in typical single-mode fibers compliant with ITU-T G.652[*]. A mode coupler is used to separate the backscattered light into individual modes and to select the mode of the probe pulses. The first-order mode at the wavelength in the 1-µm band is more sensitive to trouble spots in optical fiber links, such as macro/micro-bends, than the fundamental mode in the communications wavelength band. Therefore, the 1-µm OTDR is very promising for finding potential trouble points before they have a serious impact on an optical communications system. The 1-µm OTDR requires an MC with low mode crosstalk to ensure sensitive detection. Here, we introduce a mode coupler that achieves high conversion efficiency and low mode crosstalk by using a multistage mode conversion method.

A schematic of the structure and operation of a conventional mode coupler is shown in **Fig. 4(a)**. The input fundamental mode from port 1 is converted to the first-order mode and output from port 4. Almost all of the fundamental mode from port 2 passes through the coupler. The fundamental mode and first-order mode are generated as backscattered light. The fundamental mode and first-order mode from port 4 can be detected separately from the mode-mixed light at ports 1 and 2. The dashed line shows the mode crosstalk path. Part of the fundamental mode from port 4 is coupled to the thin waveguide with the fundamental mode and output from port 1 as a noise component.

To solve this noise component problem, we developed a coupler with high conversion efficiency and

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[*] ITU-T G.652: Recommendation issued by the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) concerning characteristics of a single-mode optical fiber and cable.

low mode crosstalk, as shown in **Fig. 4(b)**. An additional mode conversion waveguide placed between the single-mode waveguide and multimode waveguide of the mode coupler indirectly converts the mode into a desired one via an intermediate mode. In this work, we chose the second-order mode as the intermediate mode. Adding the second-order mode enhances the mode isolation and reduces mode crosstalk. Setting the waveguide width correctly ensures that no additional loss occurs due to adding the waveguide.

The measured conversion efficiency of the coupler fabricated using PLC technology is plotted in **Fig. 4(c)**. The conversion efficiency is −0.8 dB at the wavelength of 1.05 µm, which is used for the 1-µm OTDR. The measured mode crosstalk is shown in **Fig. 4(d)**. The mode crosstalk is under –30 dB. These results confirm that we succeeded in making a mode coupler with high conversion efficiency and low mode crosstalk by using a multistage mode conversion method.

5. Future prospects

This article introduced optical multimode devices that use PLC technology. We showed that by using the mode as a new degree of freedom of light, we can miniaturize waveguide devices and achieve high performance. Establishing design, manufacturing, and evaluation technologies for handling modes will pave the way for the implementation of unprecedented optical devices with new functions and unique properties.

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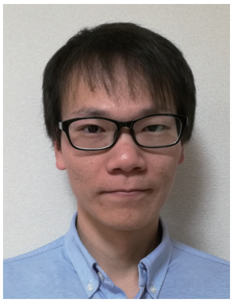

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Standardization Efforts of International Electrotechnical Commission Related to Surge Protection Components, and Receipt of METI Minister's Award

Hidetaka Sato

Abstract

An International Electrotechnical Commission (IEC) international standard for surge isolation transformers (SITs) for communications use has been established based on a proposal from Japan. SITs are components featuring high insulation-breakdown voltage and impedance. They reduce lightning surges to a small voltage level so there is no effect on protected equipment, while simultaneously blocking a common mode noise loop. They provide excellent protection for the DC (direct current) SELV (safety extra-low voltage) circuit on the secondary side in information and communication technology equipment. This article introduces international standardization activities related to SITs at IEC and discusses associated technology.

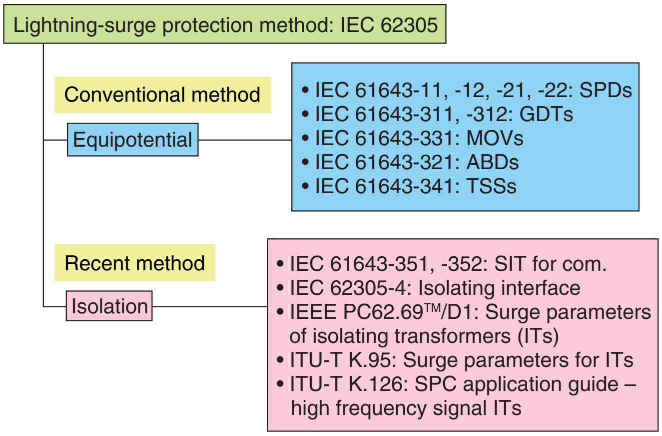
Keywords: lightning protection, self-contained isolation system (SIS), surge isolation transformer

1. Introduction

There is an ongoing need to protect electronic equipment from damage caused by lightning surges, and therefore, research on technology to achieve this continues. In this section, issues that have become newly apparent are introduced.

1.1 Emergence of new issues

Lightning protection measures up to now have mainly focused on preventing permanent damage or fires caused by burning, scorching, or melting as a result of an insulation breakdown within information and communication technology (ICT) equipment and electric/electronic appliances triggered by overvoltage or overcurrent surges caused by lightning. Today, advances in lightning protection technology have reduced equipment damage due to overvoltage breakdown in hardware, but data errors have recently become evident as a new form of lightning-related damage. This is a phenomenon in which errors occur in data being processed even if the hardware itself has suffered absolutely no damage. It can give rise to problems such as corruption of original data, equipment freezing, system hang-ups, malfunctions, out-of-control operation, and system downtime. In the event of such a problem, it is usually possible to restore operation by resetting the equipment, turning power OFF/ON (rebooting), reloading the operating system, or restoring (salvaging) corrupted data. Nevertheless, such lightning-related data errors run the risk of lost opportunities, disappearance of immediately previous data deliverables, and failure to notice that data errors lay hidden within memory. While data errors that occur during data reading or transfer can usually be handled by error-correcting code, the need has arisen for more robust measures against data errors that occur at the time of a lightning strike.



Com.: communications

Fig. 1. Equipotential and isolation lightning-surge protection methods and their international standards.

1.2 Problem with Japan's isolated earth environment

Surge isolation transformers (SITs) have been widely used in Japan's power supply system for some time. They are known as lightning-resistance transformers, and they have rarely been used outside Japan. To give some background, while Japan focused on isolated-earth systems, the trend overseas was integrated-earth systems and lightning protection by equipotential methods such as using the earth as a reference point. For example, grounding for communications in Japan has been achieved by installing subscriber arresters for communications use in all telephone subscriber homes, but this method involves the independent grounding of subscriber arresters in isolation from the grounding of power systems, buildings, and other elements. As a result, the following problem arises with Japan's isolated earth environment: if a lightning surge flows in one such earth connection, an earth potential rise occurs due to earth resistance, resulting in a new overvoltage surge source.

The International Electrotechnical Commission (IEC) has been active in developing standards for surge protective devices (SPDs) and surge protective components (SPCs) used in equipotential methods, and the development of standards for isolation methods has been progressing at the Institute of Electrical and Electronics Engineers (IEEE) and International Telecommunication Union - Telecommunication Standardization Sector (ITU-T).

2. Overview of IEC committee organization

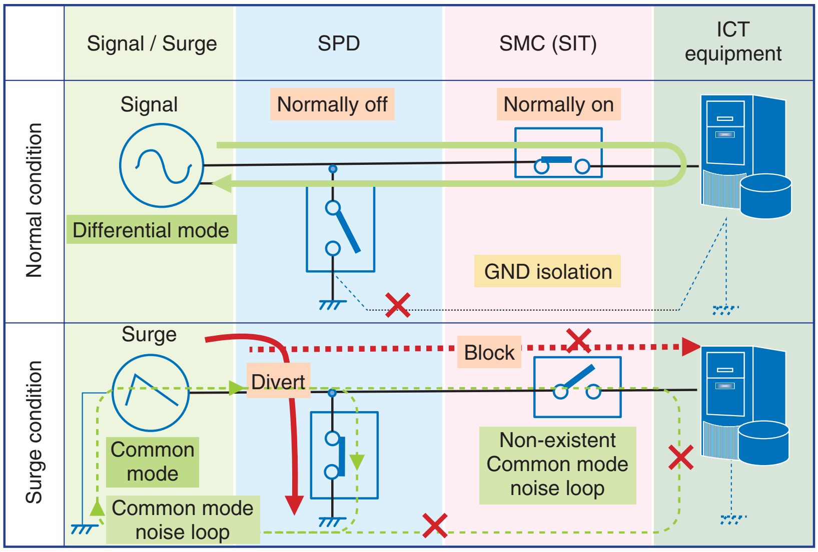
The IEC committee and Working Group addressing the standardization of technology in this area are introduced in this section.

2.1 IEC/SC 37B organization

IEC Technical Committee (TC) 37 (surge arresters)/ Subcommittee (SC) 37B (components for low-voltage surge protection) is a group working to establish IEC international standards on discrete surge-protection components that reduce lightning surges to a sufficiently small level to protect the human body, equipment, and appliances. Four international standards have been established so far: IEC 61643-311: GDTs (gas discharge tubes); IEC 61643-321: ABDs (avalanche breakdown diodes); IEC 61643-331: MOVs (metal oxide varistors); and IEC 61643-341: TSSs (thyristor surge suppressors) (**Fig. 1**). All of these standards concern components for achieving overvoltage protection through lightning equipotential methods using the voltage non-linear resistance characteristics of these SPCs. In relation to the above, Japan submitted a new work item proposal (NP) on SITs as a fifth type of SPC using an isolation method completely different from the above equipotential methods.

2.2 Overview of Working Group (WG) 3 project activities

The initial 2010 NP and CD (committee draft) was approved by international vote, but since the participation of at least four overseas experts required for



GND: ground

Fig. 2. Lightning-surge overvoltage and common mode noise protection using SIT and SPD.

establishing a project could not be obtained from the 14 participating members (P-members), Japan's proposal for a new IEC project was rejected. We attributed this to the low international awareness of SITs. We therefore conducted an information campaign over the next two years to heighten worldwide awareness, and by resubmitting the NP in 2012, we succeeded in establishing an IEC 61643-351/352 project through the participation of experts from the four countries of China, Germany, the United Kingdom, and Japan. IEC/SC 37B/WG 3 (surge isolation transformers) was then established with the author as convenor, and standardization work began.

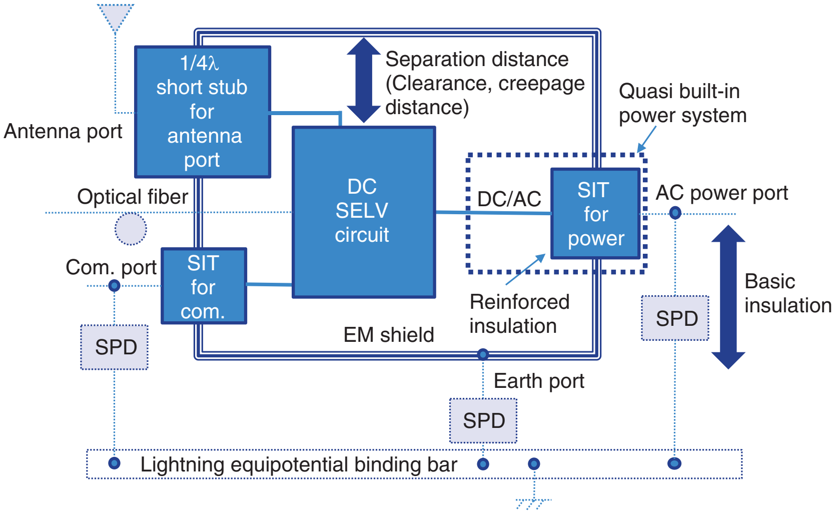
At the same time, France and the United States opposed this project for the reason that SITs were outside the scope of SC 37B. They argued that the scope of IEC SC 37B, the parent subcommittee, is components for use as SPDs, and the definition of an SPD was "a device incorporating one or more nonlinear elements having the purpose of limiting surge voltage and diverting surge current," so SITs, having no non-linear elements, were outside the scope.

A revision to the scope of SC 37B was therefore proposed by Japan at the 2013 plenary meeting and discussions, and the result of an international vote produced the following new scope: "To prepare international standards for components for low-voltage surge protection. These SPCs are used in power, telecommunication and/or signaling networks with voltages up to 1000 V a.c. and 1500 V d.c."

In other words, all components that reduce surge, or SMCs (surge mitigation components), were now to be handled by SC 37B, and on the basis of this revision, France and the United States became involved as experts. Additionally, an IEC NP in relation to SITs proposed by Japan was introduced at the ITU-T SG5 (Study Group 5: environment and circular economy) meeting in Geneva held from April 26 to May 3, 2011. As a result, even ITU-T came to recognize the need for SITs, and thus, SIT-related activities progressed with a liaison member.

3. Lightning protection of ICT equipment by SITs for communications

An example of a countermeasure to lightning overvoltage surge protection and common mode noise combining an SPD (equipotential method) and SIT (isolation method) is shown in **Fig. 2** using equivalent switch circuits. Here, the SPD and SIT operate in an exclusive and complementary manner. The SPD requires grounding to achieve equipotential surge protection. In the event of a surge, it immediately turns the switch ON to form a path that diverts the surge current to earth. At this time, a large-area common mode noise loop including the earth forms, resulting in a noise source that can generate data errors, and an earth potential rise occurs due to earth



AC: alternating current
DC: direct current
EM: electromagnetic

Fig. 3. Self-contained isolation system for DC SELV (direct current safety extra-low voltage) circuit in ICT and Internet of Things equipment.

resistance. These are weak points of this device.

However, the SIT turns OFF under a surge condition, thereby blocking a common mode surge current and dramatically improving noise resistance from an electromagnetic compatibility perspective. Thanks to its high insulation-breakdown voltage, a SIT can treat its primary-side and secondary-side ground (GND) potentials as different, thereby achieving GND isolation.

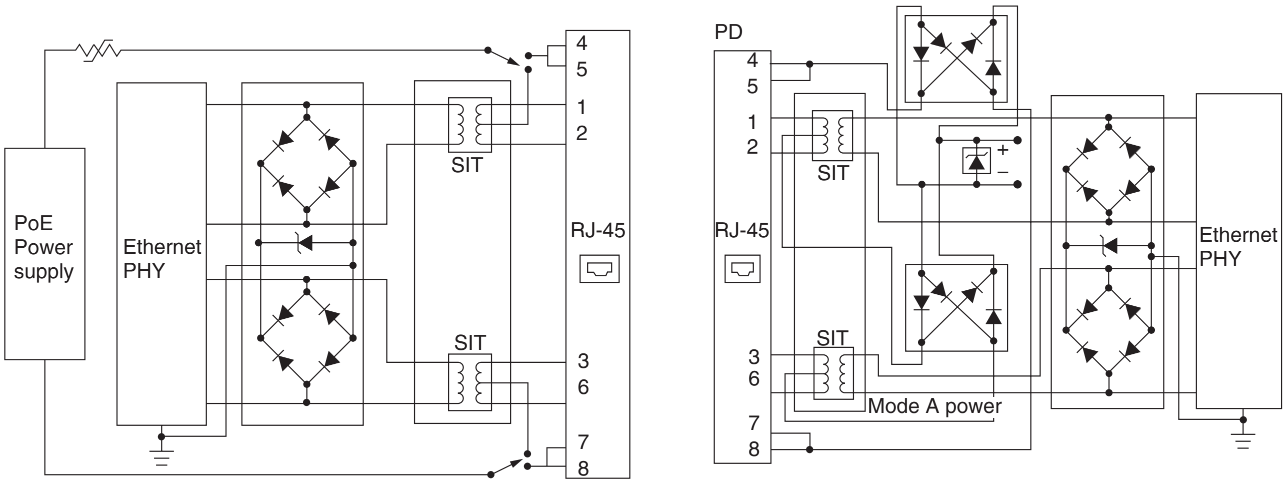
An example of the application of a SIT to ICT equipment is shown in **Fig. 3** and to Ethernet communications in combination with a direct current (DC) power feed is shown in **Fig. 4**. The ICT equipment on the secondary side usually features a DC safety extra-low voltage (SELV; not exceeding a peak value of 42.4 V or DC 60 V) circuit that requires no grounding when used in combination with insulation, enabling it to be set at a floating potential. In conventional SPD multistage protection, the let-through current that flows due to SPD coordination becomes a powerful common mode noise source that has been the cause of data errors in ICT equipment. The combined SPD and SIT block common mode noise by virtue of the SIT and drastically reduce surge voltage migration to 1/100–1/1000 of the SPD peak voltage. It is therefore an excellent countermeasure to both lightning overvoltage surges and data errors.

4. METI Minister’s Award

The author received the 2018 Ministry of Economy, Trade and Industry (METI) Minister’s Award in Industrial Standardization in recognition of the following activities: submitting Japan’s proposal for IEC/TC 37/SC 37B/WG 3 and serving as convenor (WG 3 international chairman); contributing to the formulation of IEC 61643-351 (SIT performance requirements and test methods) and IEC 61643-352 (SIT selection and application principles); and in anticipation of artificial intelligence (AI), Internet of Things (IoT), and big data connections that are expected to expand on a global scale, formulating international standards for lightning protection measures in SELV ICT equipment connected to the Internet, thereby making Japan a forerunner in this endeavor and enhancing the country’s international industrial competitiveness.

5. Future plans

In recent years, studies have been accelerating on Industry 4.0 (transformation of the manufacturing industry through IoT and AI technologies) and the international standardization of ISO (International Organization for Standardization) 8000 (data quality) with an eye to achieving the Society 5.0 vision [1].



PHY: physical layer

(a) PSE (power sourcing equipment) side

(b) PD (power device) side

Fig. 4. SIT application example for PoE (Power over Ethernet) communication.

From here on, as the use of big data expands and IoT and AI spread throughout society, we can expect data quality to become all the more important in industrial, service, and medical-care fields and in databases released by government and public institutions. In addition to simultaneously supporting lightning overvoltage surge protection and data quality, the SIT is a leading component embodying the idea of a self-contained isolation system [2], similar to that of airplanes, having a proven record in withstanding direct lightning strikes and lightning electromagnetic waves. With this in mind, we plan to proceed with the IEC international standardization of SITs for power supply systems.

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He received a B.E. from Iwate University in 1981 and a Ph.D. from Tohoku University in 1995. In 1981, he joined Musashino Electrical Communications Laboratories of the Nippon Telegraph and Telephone Public Corporation (now NTT), in Musahino-shi, Tokyo. He was a visiting professor at the University Technology Malaysia (UTM) in 1996 and returned to the NTT laboratories in 1997. He is currently affiliated with the research and development (R&D) division of NTT Facilities, where he has been engaged in R&D of lightning protection technologies and their standardization as chairman of IEC SC37A and SC37B Japanese National Committee. He received the METI Minister's Award in 2018, and IEC 1906 Awards in 2013 and 2018. He is a Professional Engineer Jp, IntPE(Jp), and APEC Engineer (Electrical). Dr. Sato is a senior member of IEEE and the Institute of Electronics, Information and Communication Engineers (IEICE), and a member of the Institute of Electrical Installation Engineers of Japan (IEIE) and the Institute of Electrical Engineers of Japan (IEEJ).

NTT Develops Non-rigid Object Recognition Technology that Achieves Recognition of Database Images—Not Only Rigid 3D Objects but also Non-rigid Objects—at Low Cost

1. Introduction

NTT has developed a new technology called *angle-free rigid and non-rigid object information retrieval*, which recognizes and searches deformable objects with a small number of database images (**Fig. 1**). This technology makes it possible to recognize rigid three-dimensional (3D) objects as well as non-rigid objects such as soft packaging or cloth products with high accuracy.

Conventionally, image recognition technologies including deep learning based ones require the preparation of many database images capturing multiple deformation patterns in order to recognize deformed objects. If an unknown deformation is added to the object, many more database images are needed to recognize it. Our new rigid and non-rigid object image matching technology recognizes an object with an unknown deformation as the same object as the non-deformed object image in the database.

With this technology, the cost of preparing database images is greatly reduced, which makes it possible to develop a product management system for a retail industry in which new products are released frequently. This is also applicable to product recognition, which saves labor in check-out operations, and product information presentation, which enables customers to browse product descriptions in multiple languages.

2. Background

To realize a digital transformation that improves our lives by connecting people with information and communication technology, it is essential to establish recognition and search technologies that can perform these functions using images taken by smartphones and cameras in place of the human eye.

However, non-rigid objects such as soft packaging products and cloth products have different patterns of deformation than rigid 3D objects. Therefore, the appearance of the images changes greatly, resulting in lower recognition accuracy. To maintain recognition accuracy, it is necessary to register the image corresponding to the deformation of the target object as a reference image. However, if the pattern of deformation of the target object is arbitrary, it is necessary to prepare a large number of images, which substantially increases the cost.

3. Research and development achievements

In the angle-free rigid and non-rigid object information retrieval technology developed by NTT, a geometric constraint is applied for each of multiple partial areas rather than for the entire object. The rigid and non-rigid object image matching accurately specifies the correct correspondence from the correspondence relationship of the image features. Thus, the correct correspondence between the input image and the reference image can be specified even if the object is deformed. As a result, it is possible to recognize and search with high accuracy not only rigid 3D objects, but also non-rigid objects in which arbitrary deformations occur.

- The conventional angle-free object information retrieval can recognize/retrieve 3D objects with high accuracy using a few registered images. However, the recognition accuracy for deformed objects decreases, as this technology assumes that the object has a fixed shape.
- Angle-free rigid and non-rigid object information retrieval can recognize/retrieve with high accuracy objects having arbitrary deformations, with just a few registered images.

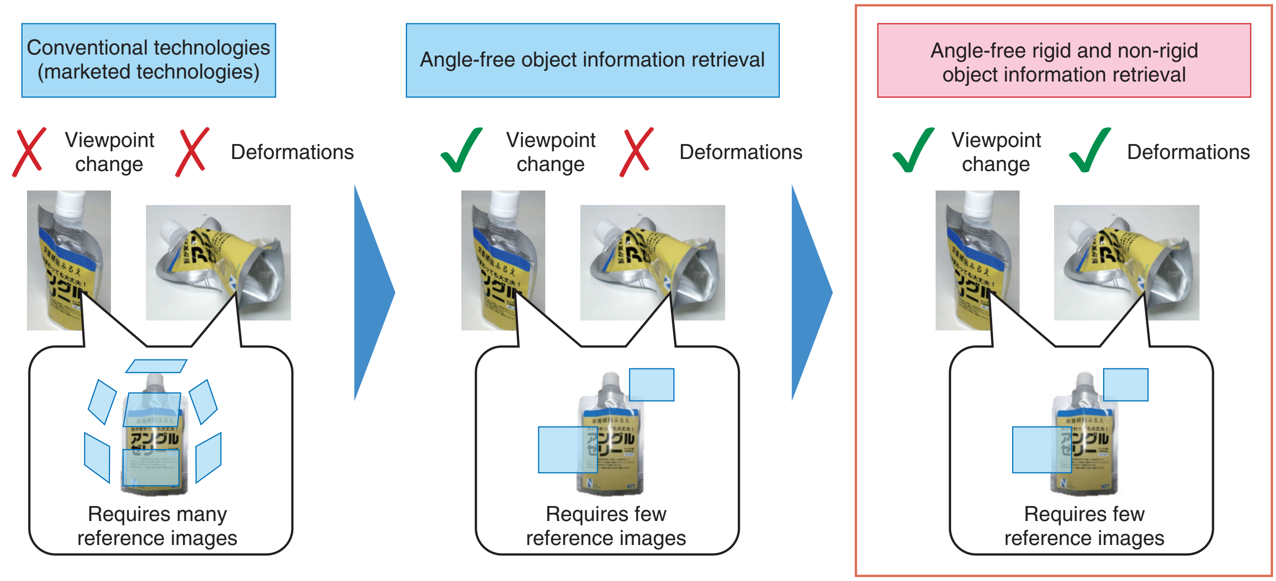

Fig. 1. Features of angle-free rigid and non-rigid object information retrieval.

4. Technical features

Angle-free rigid and non-rigid object information retrieval is an NTT corevo® artificial intelligence technology that was developed based on angle-free object information retrieval, a technique for recognizing and searching 3D objects only by registering images from a few directions. The features of this technology are as follows.

In the conventional angle-free object information retrieval, the recognition accuracy deteriorates for deformed objects because the constraint condition on the same object is derived from the projective geometric examination based on the assumption that the object has a fixed shape. Furthermore, with existing learning based methods such as those based on deep learning, if a non-rigid object is used as a target, the recognition accuracy also deteriorates, since there are countless deformation patterns, unless a large number of reference images observing various deformations are prepared in advance.

Therefore, *rigid and non-rigid object image matching* has been developed, which accurately specifies the correct correspondence from the correspondence of the image features by applying the geometric constraint to multiple partial regions instead of to the entire object. This makes it possible to specify the correct correspondence even if the object is deformed, by clustering using geometric features such as distances and rotation angles between multiple correspondence relationships based on the correspondence result of image features between the input image and the reference image. NTT's angle-free rigid and non-rigid object information retrieval expands this technology, making it possible to achieve recognition and retrieval with high accuracy by only registering a small number of images even if the pattern of deformation is arbitrary.

For Inquiries

Public Relations,
NTT Service Innovation Laboratory Group
http://www.ntt.co.jp/news2018/1811e/181126b.html

External Awards

Best Paper Award

Winner: Yuiko Tsunomori, NTT DOCOMO, INC.; Ryuichiro Higashinaka, NTT Media Intelligence Laboratories; and Takeshi Yoshimura, NTT DOCOMO, INC.
Date: February 21, 2019
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE) Technical Committee on Natural Language Understanding and Models of Communication (NLC)

For "A Long-term Evaluation of a Chat-oriented Dialogue System that Utilizes User Information Acquired through Dialogue."
Published as: Y. Tsunomori, R. Higashinaka, and T. Yoshimura, "A Long-term Evaluation of a Chat-oriented Dialogue System that Utilizes User Information Acquired through Dialogue," IEICE Tech. Rep., Vol. 118, No. 122, NLC2018-4, pp. 29–34, July 2018.

Maejima Hisoka Award

Winner: Masayuki Abe, NTT Secure Platform Laboratories
Date: February 26, 2019
Organization: Tsushinbunka Association

For his pioneering research on secure and user-friendly electronic signatures and cryptographic protocols.

IEICE Information Networks Best Research Award

Winner: Yasuhiro Ikeda, Keisuke Ishibashi, Yuusuke Nakano, Keishiro Watanabe, and Ryoichi Kawahara, NTT Network Technology Laboratories
Date: March 4, 2019
Organization: IEICE Technical Committee on Information Networks (IN)

For "Retraining Anomaly Detection Model Using Autoencoder."
Published as: Y. Ikeda, K. Ishibashi, Y. Nakano, K. Watanabe, and R. Kawahara, "Retraining Anomaly Detection Model Using Autoencoder," IEICE Tech. Rep., Vol. 117, No. 397, IN2017-84, pp. 77–82, Jan. 2018.

IOP Publishing Outstanding Reviewer Award 2018

Winner: Xuejun Xu, NTT Basic Research Laboratories
Date: March 13, 2019
Organization: IOP Publishing Limited

For his outstanding work as a reviewer of semiconductor science and technology in 2018.

TELECOM System Technology Award

Winner: Hideki Maeda, Kohei Saito, Takashi Kotanigawa, Takeshi Seki, NTT Network Service Systems Laboratories; Shuto Yamamoto, Fukutaro Hamaoka, NTT Network Innovation Laboratories; and Mitsuteru Yoshida, NTT Electronics Corporation
Date: March 20, 2019
Organization: The Telecommunications Advancement Foundation

For "Field Trial of 400-Gbps Transmission Using Advanced Digital Coherent Technologies."
Published as: H. Maeda, K. Saito, T. Kotanigawa, T. Seki, S. Yamamoto, F. Hamaoka, and M. Yoshida, "Field Trial of 400-Gbps Transmission Using Advanced Digital Coherent Technologies," J. Lightw. Technol., Vol. 35, No. 12, June 2017.

Young Researcher's Award

Winner: Toshiro Nakahira, NTT Access Network Service Systems Laboratories
Date: March 21, 2019
Organization: IEICE

For "802.11ax Based Multi-RF Control Method for WiSMA" and "Spatial Resource Optimization under Multi-interface Control Scheme on Strategy Management Architecture for Wireless Resource Optimization (WiSMA)."
Published as: T. Nakahira, T. Murakami, H. Abeysekera, K. Ishihara, A. Inoki, K. Wakao, Y. Takatori, and T. Hayashi, "802.11ax Based Multi-RF Control Method for WiSMA," Proc. of the 2018 IEICE General Conference, B-5-135, Tokyo, Japan, Mar. 2018 (in Japanese). T. Nakahira, H. Abeysekera, T. Murakami, K. Ishihara, and T. Hayashi, "Spatial Resource Optimization under Multi-interface Control Scheme on Strategy Management Architecture for Wireless Resource Optimization (WiSMA)," Proc. of the 2018 IEICE Society Conference, B-5-96, Kanazawa, Ishikawa, Japan, Sept. 2018 (in Japanese).

Young Researcher's Award

Winner: Akito Suzuki, NTT Network Technology Laboratories
Date: March 21, 2019
Organization: IEICE

For "Evaluation of Routing Control Method Utilizing External Information on Large-volume Traffic Generation" and "Applicability Evaluation of NFV-integrated Control Method Using Reinforcement Learning."
Published as: A. Suzuki, M. Kobayashi, S. Harada, and R. Kawahara, "Evaluation of Routing Control Method Utilizing External Information on Large-volume Traffic Generation," Proc. of the 2018 IEICE General Conference, B-7-22, Tokyo, Japan, Mar. 2018 (in Japanese). A. Suzuki, M. Kobayashi, S. Harada, and R. Kawahara, "Applicability Evaluation of NFV-integrated Control Method Using Reinforcement Learning," Proc. of the 2018 IEICE Society Conference, B-7-12, Kanazawa, Ishikawa, Japan, Sept. 2018 (in Japanese).

Papers Published in Technical Journals and Conference Proceedings

Live Line Aging Estimation of AC Adapters

F. Ishiyama and Y. Toriumi

Proc. of the 18th IEEE International Symposium on Signal Processing and Information Technology (ISSPIT 2018), pp. 175–178, Louisville, KY, USA, December 2018.

There is a risk that highly deteriorated alternating current (AC) adapters may ignite and catch fire. If we could estimate the extent of aging using live line measurement, we would be able to find deteriorated AC adapters without interrupting the operation of electrical equipment. As we know that deteriorated AC adapters cause electromagnetic noise on power lines, we conducted a study to ascertain if we could estimate the extent of aging from the intensity of the noise. We found that this was possible using our method of time series analysis, which has extremely high time-frequency resolution. In this paper, we describe our method and present the results of the analysis.

Intelligent Monitoring of Optical Fiber Bend Using Artificial Neural Networks Trained with Constellation Data

T. Tanaka, W. Kawakami, S. Kuwabara, S. Kobayashi, and A. Hirano

IEEE Networking Letters, DOI: 10.1109/LNET.2019.2897295, February 2019.

We demonstrate, for the first time, the highly accurate detection of the physical condition of optical fiber by using an artificial neural network (ANN). The ANN takes constellation data as its input, and outputs estimation data indicating the presence of optical fiber bending. This technique can estimate optical fiber condition without additional testers. We verify that the trained ANN can precisely detect optical fiber bends from test data as well as validation data in transmission lines with no optical amplifiers. The proposal is effective if optical amplifiers are used provided the amplitude spontaneous emission noise is small.

Economical Speed Adjustment Scheme Based on Deep Reinforcement Learning

M. Yoshida, K. Mizutani, T. Hata, I. Shake, and T. Kashiwai

Transactions of Society of Automotive Engineers of Japan, Vol. 50, No. 2, pp. 622–628, March 2019 (in Japanese).

In this paper, we report on a deep reinforcement learning technique that outputs the optimum speed acceleration to improve fuel economy while taking into account traffic flow on a public highway. The deep reinforcement learning utilizes the distance of spatiotemporal features of traffic signal conditions. From the simulation evaluation of our scheme, we confirmed that fuel efficiency can be improved by about 10% while maintaining the overall traffic flow with the proposed method, compared to the rule-base speed adjustment scheme.

Development of Resilient Information and Communications Technology for Relief against Natural Disasters

H. Kumagai, H. Sakurauchi, S. Koitabashi, T. Uchiyama, S. Sasaki, K. Noda, M. Ishizaki, S. Kotabe, A. Yamamoto, Y. Shimizu, Y. Suzuki, Y. Owada, K. Temma, G. Sato, T. Miyazaki, P. Li, Y. Kawamoto, N. Kato, and H. Nishiyama

Journal of Disaster Research, Vol. 14, No. 2, pp. 348–362, March 2019.

The study focused on the research and development of information and communication technology (ICT) for disaster preparedness and response with respect to two categories, namely, the delivery of alert messages to a wider group of residents and providing quick relief communications in affected areas. In the former category, the development focused on two targets, one involving the delivery of alert messages to indoor residents with a V-Low broadcasting service and the other involving the delivery of an alert message to individuals with disabilities and difficulties in understanding Japanese. In the latter category, a portable ICT unit was developed for rapid relief communications, and mesh network technology enabling robust information sharing among base stations in the affected area was developed. Furthermore, a related development focused on a resilient information management system to collect information in areas that do not have access to the Internet. Furthermore, device relay technology was developed to expand access network coverage areas. After the development of individual technology, activities for the societal implementation of the development results were conducted through field experiments and disaster drills in which the developed technologies were integrated and utilized.
