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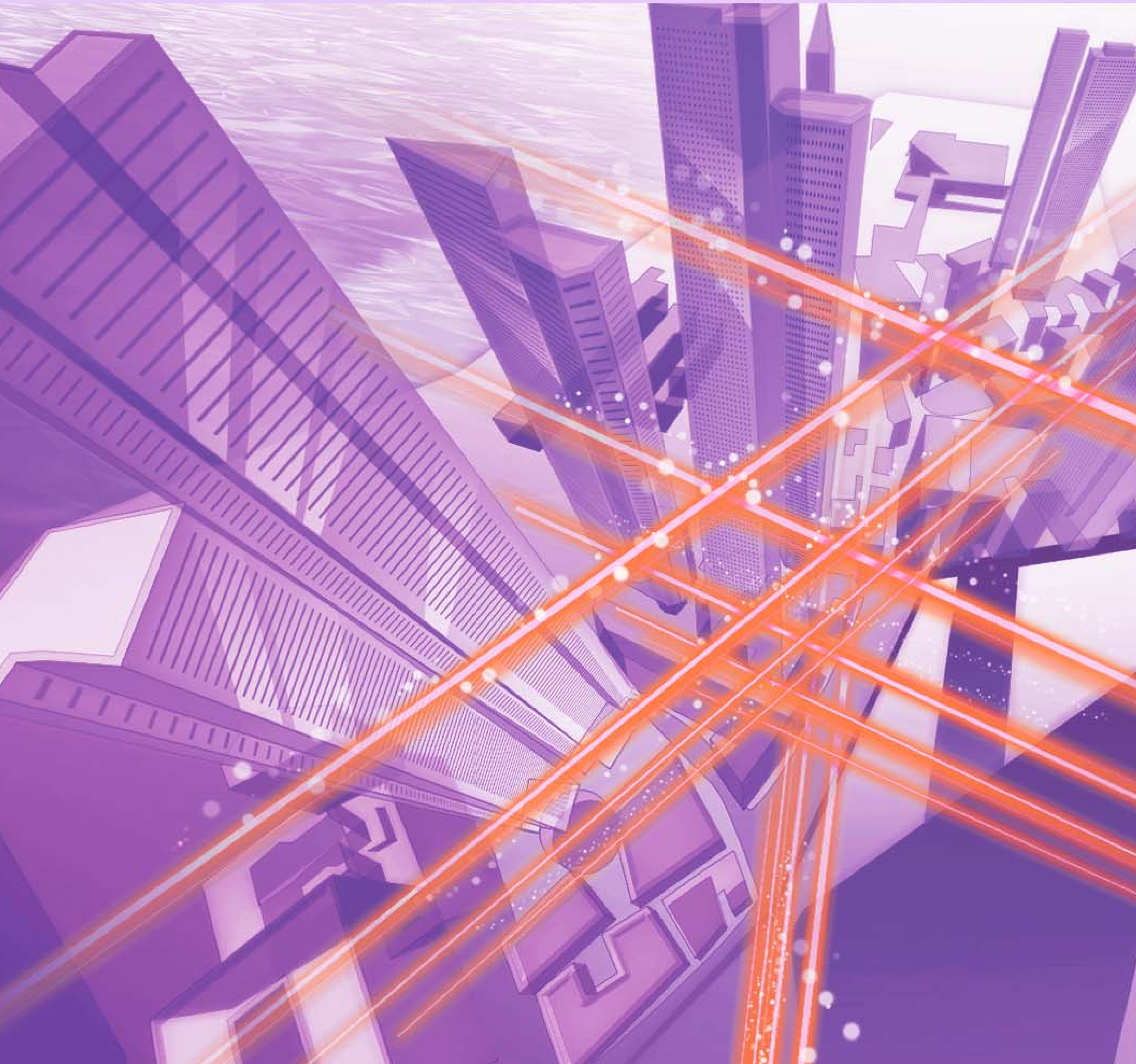

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NTT Technical Review

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People Are the Starting Point for All New Services and Products

Akira Shimada
President and Chief Executive Officer, NTT

Abstract

With people at its core, the NTT Group defines the capabilities it aims to achieve as service expertise, technical expertise, and intelligence. All 330,000 NTT Group employees—working in approximately 90 countries and regions—are accelerating the group's self-transformation into a new NTT that is open, global, and innovative to be valuable to all stakeholders, including customers, shareholders, local communities, and employees. We asked Akira Shimada, president and chief executive officer of NTT, who took up the post in June 2022, about the details of the guidelines that he announced at his inaugural press conference and his thoughts on what it means to be a top executive.

Keywords: customer experience, employee experience, carbon neutrality

Accelerating our self-transformation and delivering new experiences and value to our customers

—Congratulations on your new position. You must be busy every day with press conferences and interviews. First, could you tell us about your vision for NTT?

As I mentioned at my inaugural press conference, I will first work on creating better CX (customer experience) through better EX (employee experience) in the current business environment. All 330,000 employees of the NTT Group worldwide are required to focus on our customers and create new experiences and value for them. Therefore, the top management needs to create an environment in which all employees are motivated to meet this requirement.

Although our business started in the field of infrastructure, we are now expanding into a wide range of businesses such as solutions and applications. For our customers, being constantly connected via telecommunications is something they take for granted that goes unnoticed, like the air we breathe. However, our employees understand the importance of their work, introduce new technologies and mechanisms, and maintain and inspect equipment and facilities daily to ensure stable connections. I recognize that this steady effort is one of NTT's strengths.

I believe that people are the starting point for all the services and products that NTT creates. Services and products do not arise spontaneously; they are created by employees in charge of research and development (R&D), maintenance and inspection, and customer service at call centers and stores who strive to satisfy customers through their originality and ingenuity when carrying out their assigned missions. In other words, people are the source of our success.

—There are high expectations for the services and products that will be created by the increased satisfaction of your employees, right?

Naturally, we face competition. If, despite our best efforts, we cannot satisfy our customers, other companies will replace us. To prevent this, we need to constantly check whether our customers are satisfied

with the services and products that we provide for them. We must always understand the viewpoint of our customers and work to improve what can be improved—even if only slightly.

We must also impress customers with new services and products, so we will attempt to provide services that give them a glimpse of the future. It is important to challenge the status quo by creating something new to adapt to an ever-changing world.

To build a foundation to support such efforts and boost employee morale, I want to create a system that recognizes employees who work hard and acquire new skills, improves the expertise of all employees, and reforms working styles. As I mentioned at my inaugural press conference, due to the COVID-19 pandemic, many of our employees have experienced remote working. Employee surveys have confirmed some positive effects of remote working, including reduced commuting burdens and improved satisfaction among employees raising children.

Remote working is allowed according to the desire of the individual employee because of the variable nature of an employee's job, experience and skills, and living environment. However, much work is completed by a team rather than one person. I, therefore, want our employees to work in a hybrid fashion combining remote and office-based working in accordance with each employee's situation. That said, I think it is essential for new employees to learn how to do their jobs, and for that reason, I hope that they come to the office to receive guidance from their supervisors and peers in person and try to build relationships with colleagues.

Reducing electricity usage through IOWN and achieving carbon neutrality

—Social contribution is an important objective for the NTT Group. Could you tell us about some of the initiatives that you will be focusing on?

The NTT Group is promoting various initiatives to create a sustainable society, and we consider energy a particularly important social issue. To address this issue, the NTT Group aims to achieve carbon neutrality by 2040. As the amount of communication continues to increase with the spread of the Internet and smartphones, the information and telecommunications industry currently consumes nearly 1% of Japan's commercial electricity consumption, and much of its greenhouse-gas emissions stem from electricity consumption.

Against that backdrop, we have set our carbon-neutrality goal ten years ahead of the one set by the Japanese government. I hope people will consider our declaration of achieving carbon neutrality by 2040 as our determination to make a concerted effort by all our employees. We will achieve this goal by reducing power consumption using photonics-based technology in everything from networks to terminals in the Innovative Optical and Wireless Network (IOWN) and developing renewable energy.

—Society also has high expectations for NTT's R&D. Would you tell us about some of NTT's world-leading or unique achievements, including IOWN?

A representative example of our achievements is photonics-electronics convergence technology, which is a component of IOWN. Currently, optical fiber is used for transmission lines and wiring between devices. However, photonics-electronics convergence technology takes this material a step further and uses photonics instead of electronics to connect circuit boards within a device, between chips and other parts on the board, and ultimately even within chips. This technology lowers power consumption and increases processing speed. It is a long-term goal, and we first plan to achieve the board-to-board optical interconnection by 2025.

We have also achieved a variety of world-class research results concerning, for example, artificial intelligence and quantum computers, which are familiar to everyone these days. One of our unique achievements is our research in the field of sports science, which contributed to the Japanese women's softball team winning the gold medal at a major international sporting event held in Tokyo in 2021. By making it possible to "train the brain and win the competition," our researchers took a practical approach in conjunction with academic research. In particular, they developed a batting-training system that combines videos of pitchers with a pitching machine that can analyze the pitch quality of opposing pitchers and throw a variety of pitches based on the analysis results and provided the system at training camps for the team.

We regularly present many of our achievements at the NTT R&D Forum, which is currently held only once a year and is by invitation only, so only a limited number of people can attend. Since these research achievements involve technologies that are not widespread, it may be difficult for the general public to understand them. Therefore, I believe it is necessary to explain our research results in an easy-to-understand manner to disseminate them in society. To that end, we are considering shooting and distributing videos of my visits to our laboratories to talk with experts and researchers in various fields.

Realizing that "what goes around comes around" while in the US

—What path did you take from the time you joined the company until you were appointed president? Did you set your sights on your current position?

When many people my age became working adults, they probably joined companies intending to reach the top. However, even though they had such a passionate aspiration, I don't think it is realistic. That was the case for me. After joining Nippon Telegraph and Telephone Public Corporation in 1981, I started working in sales at a telephone exchange. The following year, I completed training in outdoor and indoor maintenance and then training in a department handling data communications, which were the main businesses of NTT at the time. After that, I was in charge of planning budgets at the Planning Department of the head office. Next, I became assistant manager of the Sales Section at the Makuhari Telegram and

Telephone Office, seconded to the then Economic Planning Agency of Japan. I then was appointed assistant manager of the Human Resources Planning Section at the head office. Afterwards, I was appointed manager of the Planning Section of the Labor Department of the Tokai Branch Office before being transferred to NTT Europe in London in 1995.

When I was in London, NTT was preparing to enter the international telecommunications market. Our first line was between Tokyo and London, and it started operating as an international data-communication line for the then Sakura Bank (now Sumitomo Mitsui Banking Corporation) on September 18, 1997. That was NTT's first global network business. As someone who has been involved in the global business from its very beginning, I am proud when I think about the fact that it has grown from almost zero sales to over a two trillion yen annual sales. I have worked for about 13 different companies within the NTT Group, both domestically and internationally, before assuming my current position. I have moved house 13 times.

My 40-plus years in the profession have not all been good ones, and I've had some tough times along the way. An example was when a US company we acquired was on the verge of financial collapse due to the bursting of the Internet bubble in the late 1990s and we had to streamline its operations to rebuild. At that time, I was working at the company branch in the US, and my views on streamlining policies did not match those of the company's top management, so I asked for suggestions from the head office in Japan. However, others discovered that I had created the original draft concerning those suggestions, and my relationship with the top management deteriorated further. That situation made it harder to do my job, but I had no choice but to carry on. From then on, I worked on increasing sales by supplying products to Japan as an OEM (original equipment manufacturer), and gradually gained the trust of several department heads, making my job easier. That experience made me keenly aware of the challenges of corporate communication and the fact that even if a company is a wholly owned subsidiary, employees of the company do not always listen to the opinions of the parent company. It also made me realize the truth in the saying "what goes around comes around."

—Thank you for sharing your experiences with us. Could you tell us about your beliefs as a top executive based on those experiences?

I believe it is essential for an organization involving many people to have good communication so that people can move in a positive direction. As a leader who works with the 330,000 employees of the NTT Group, I want to value people. A leader cannot do anything alone. The appeal of the existence of a company is that it is an organization with many people. In an organization, together we can overcome what one cannot overcome alone.

The role of the leader is to energize the organization to generate new ideas, and to fulfill that role, should not take an arrogant and formal attitude. If you take such an attitude, no one will want to talk to you. I want to be open-minded to encourage anyone to talk with me.

For those at the top management, it is our job to “discover” people. There may be people in our group who have a variety of ideas but go unnoticed. It is important to seek out such people. We must also transform our group by combining completely different organizations and people with various skills to promote innovation.

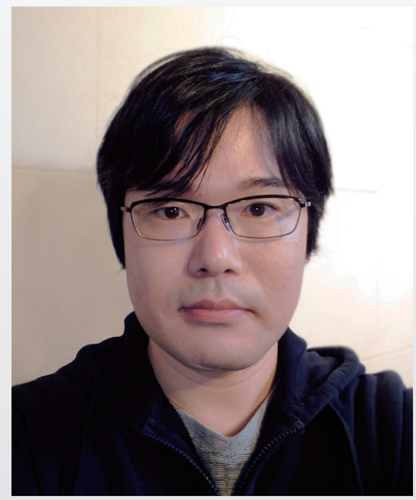
Interviewee profile

■ Career highlights

Akira Shimada joined Nippon Telegraph and Telephone Public Corporation (now NTT) in 1981. He became vice president of the Corporate Strategy Planning Department of NTT in 2007; senior vice president and member of the Board of NTT EAST in 2011; senior vice president, head of the General Affairs Department, and member of the Board of NTT in 2012; executive vice president, head of the General Affairs Department, and member of the Board of NTT in 2015; and senior executive vice president and representative member of the Board of NTT in 2018. He has held his current position since June 2022.

I Would Like to See a World in Which All Engineers Have a Cybersecurity Background

Mitsuaki Akiyama
Senior Distinguished Researcher,
NTT Social Informatics Laboratories



Abstract

NTT laboratories have a long history of research and development (R&D) in the field of computer science, including the world's most-advanced cryptography and cybersecurity. Senior Distinguished Researcher Mitsuaki Akiyama is conducting R&D on cybersecurity by incorporating social science, such as social value, people's happiness, legal systems, and social acceptability, to transform and develop society. We asked him about the progress of his research and attitude as a researcher.

Keywords: socio-technical system, usable security, research ethics

Pursuing a *socio-technical system* that is based on relationships and interactions among technology, people, and society

—It has been three years since your last interview in 2019. How have your research activities been going since then?

Continuing from our last interview, I have been researching cybersecurity to protect the safety and security of users from cyber-attacks. I'm focusing on four key themes: (i) research on analyzing the characteristics of cyber-attacks, accumulating such information (i.e., intelligence for cyber-attack countermeasures), and using this information to prevent similar attacks in the future; (ii) research on *offensive security* to stop attacks before they happen by finding and dealing with potential security and privacy threats and flaws (such as bugs in systems and services) from the attacker's viewpoint; (iii) activities related to ethics in research on cybersecurity to ensure that the results of advanced research properly benefit society, including experimental methods for discovering security and privacy threats and methods for disclosing discovered threats; and (iv) research on *usable security* to design systems that prioritize security threats and help users recognize such threats and make safer decisions by quantifying these threats according to users' security and privacy awareness and behavior toward systems and services.

In July 2021, NTT laboratories were reorganized, and NTT Social Informatics Laboratories was established. Considering it necessary to proceed with research and development (R&D) in various fields in a more composite manner, NTT Social Informatics Laboratories is engaged in a variety of research projects. These include (i) well-being research for human happiness; (ii) innovation technology for social systems through the fusion of information and communication technology (ICT) technology and social science; (iii) establishment of new technologies to eliminate threats such as cyber-attacks; (iv) establishment of technologies to realize innovations to create safe social systems through the analysis and prediction of social information; (v) creation of high-value-added social systems through data distribution and utilization that balances usability and security; (vi) new data protection technology that utilizes cryptography as well as physical properties; and (vii) creation of fundamental next-generation cryptography theories that will lead global expansion [1].

Cybersecurity has often been regarded as a cost factor. At NTT Social Informatics Laboratories, we are breaking away from this mindset. That is, we are engaged in R&D on cybersecurity technology that acts as a "prime mover" to drive and develop people and society by maintaining security and privacy. Accordingly, I'm taking advantage of the opportunity to pursue my research activities at this lab and increasing the weight of interdisciplinary aspects, such as human behavior and social aspects, in my research compared with the past. As people are forced to use new technologies without having sufficient knowledge of their security and privacy, new security and privacy threats are emerging. Under these circumstances, I believe there is an emerging need to establish a scientific foundation for cybersecurity and an approach to solving problems concerning cybersecurity from an interdisciplinary perspective.

In the industrial sector, for example, cybersecurity technology has been dominated by symptomatic and empirical measures and operations against daily cyber-attacks. Such reactive measures require an endless amount of operations, which results in increased personnel costs, slow response, and security fatigue and makes it difficult to maintain a reliable ICT system against increasingly sophisticated cyber-attacks. To create a fundamental solution that eliminates this problem, I believe it is important to create cybersecurity technologies that are transparent, reproducible, and verifiable through means such as theoretically sound mathematical and scientific methods, comprehensive theory of cybersecurity, principled system-design methods, modeling at various layers and scales for complex and dynamic systems, and creating indices to evaluate the effectiveness of cybersecurity technologies.

From the perspective of an interdisciplinary approach, I'm also pursuing a *socio-technical system* that is based on the relationships and interactions among technology, people, and society. Even if a technology is secure, it may not be secure if people use it incorrectly, and if it does not become widely used in society, people will not be able to fully benefit from it. Although many security technologies have been devised, many have never been fully used. There are many cases in which end-users are deceived by phishing scams or a technology was not properly used because the reasons for issues, such as the difficulty of implementing security-by-design in development projects, had not been clarified.

In view of these issues, I've been adopting an interdisciplinary approach that incorporates fields, such as social science and social psychology, in addition to computer science to clarify the root causes of cybersecurity problems from the viewpoints of humans and society and review ICT systems from their design phase. To achieve usable security, I'm aiming to solve security and privacy problems that depend on people's perceptions and decision-making so they cannot be solved simply by focusing on systems. Solving such problems involves the following process: (i) observing and analyzing human behavior, mental models, and decision-making processes regarding security and privacy, (ii) feeding the findings of the observation and analysis back to system design, implementation, and operation, and (iii) enabling people to make appropriate decisions on the basis of correct perceptions about security and privacy.

To make this process feasible, I believe it is essential to properly observe and analyze people's behavior and perceptions, and I am researching measures to prevent the spread of false information. False information includes *misinformation*, which is spread unintentionally, and *disinformation*, which is spread with the intent to cause harm or deceive. The spread of misinformation and disinformation through social media represents the next generation of cyber-attacks that threaten correct human cognition and judgment. It is not limited to individual problems such as falling victim to phishing or being deceived by hoaxes; it can have a major impact on democracy, as in the case of the 2016 US presidential election.

Our papers highlighting social issues were accepted by prestigious conferences

—You have achieved significant academic results through these research activities.

Our paper on offensive security was accepted at the

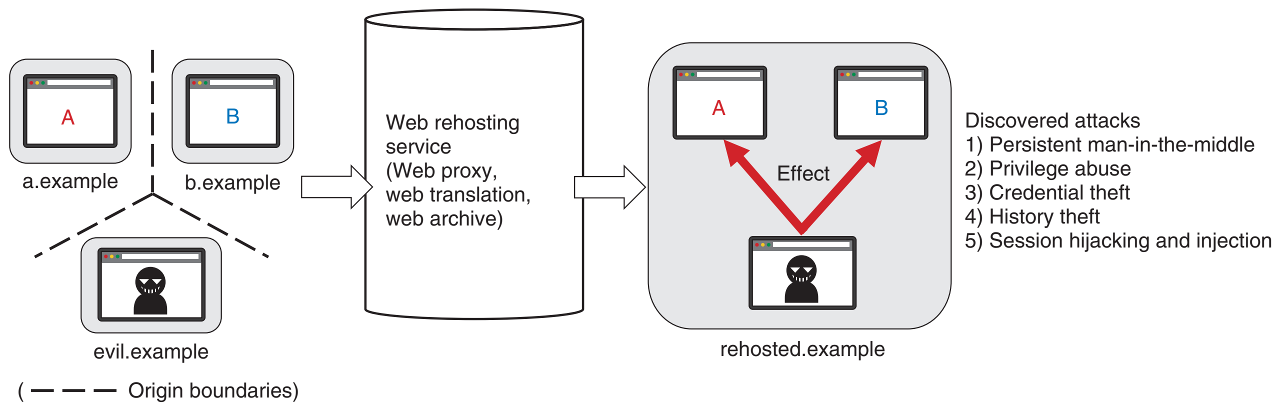


Fig. 1. Potential threats to web rehosting services.

27th Annual Network and Distributed System Security Symposium (NDSS 2020), one of the top cybersecurity conferences, and received the Distinguished Paper Award [2]. We named a service that rehosts web content on another web site a web rehosting service, developed multiple threat models for web rehosting services, and clarified, through verification, the conditions under which the threats are actually manifested (**Fig. 1**).

We discovered a critical phenomenon concerning web rehosting services; namely, the mechanisms underlying web security fail to work when web content from different origins (i.e., attributes defined by URL protocol, host, port pairs) are merged into the same origin. This discovery indicates that a variety of attacks are possible in web rehosting services, and appropriate design guidelines for web services to avoid such attacks can be provided.

This research has made it possible to detect threats before they become apparent and take countermeasures against them at the design phase. It is thus possible to avoid service operators having to redesign a service as a whole. Our goal is not to simply find vulnerabilities but to establish a more-versatile verification method and theoretical foundation for finding such security and privacy threats. With that goal in mind, we have identified many threats on the web, where various types of communication are currently aggregated, and established methods for verifying them. I hope to summarize our findings in about five years.

Regarding usable security, our research aimed at enabling secure software development focusing on developers and development projects was selected for presentation at the 37th Annual Computer Security Applications Conference (ACSAC 2021) [3]. This research was based on a large-scale online survey of professional software developers in Japan and the United States to identify organizational issues such as whether a decision-making authority exists and difficulties in decision-making (**Fig. 2**).

Our paper on explaining the principles of human deception and creating appropriate support technologies was accepted at the 17th Symposium on Usable Privacy and Security (SOUPS 2021) [4]. While previous research implicitly studied perceptions and behaviors of users when confronted with phishing emails in their native language, we focused on non-native English speakers, who make up the majority of the world's population, confronting English phishing emails. For the first time in a large-scale study, we clarified the relationship between language and handling phishing emails and proposed support techniques specific to non-native English speakers.

At European Symposium on Usable Security (EuroUSEC) 2021, our paper indicating problems in user-study methods regarding why people are deceived with respect to phishing emails received the Best Paper Award [5]. The study revealed for the first time that several methods used for screening participants in user studies are highly inconsistent because they exclude careless participants who are easily deceived by phishing emails, namely, those whose data are most needed. Another paper of ours, presenting research on countermeasures against the spread of false information in social media, was accepted at the 7th International Winter School and Conference on Network Science (NetSci-X 2022) [6], and some of the results of that research were exhibited and reported at the NTT R&D Forum.

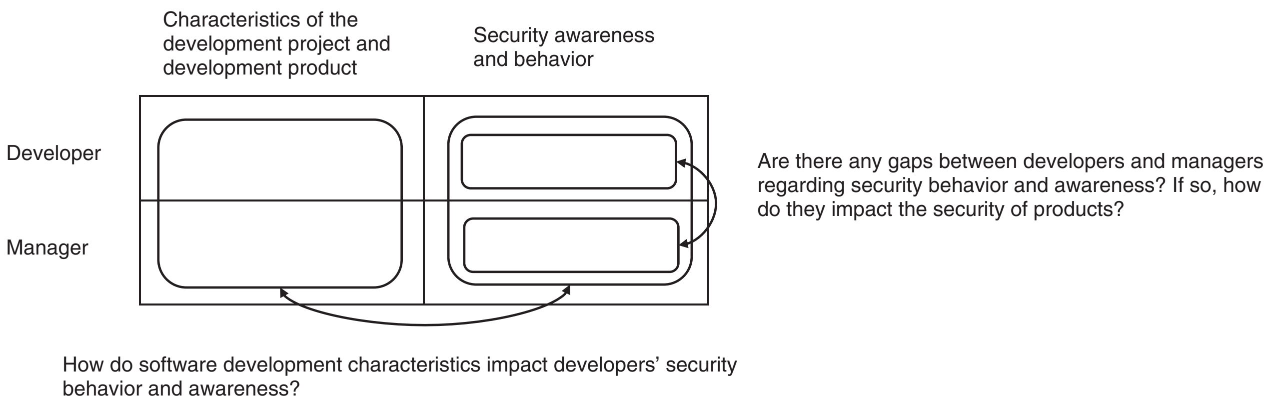


Fig. 2. Analysis of factors that hinder secure software development.

You become good at what you like doing

—What do you keep in mind and consciously implement when looking for research themes?

First, I try to be interested in new technologies and services while constantly updating my knowledge. Rather than thinking about a technology alone, I consider how such technology is used from the perspective of the people, organizations, and society involved with the technology as well as laws and ethics.

I also value having discussions with experts in fields different from mine. Since it is common to go beyond one's field of expertise when attempting to achieve something, it is essential to collaborate with researchers in other fields and adopt an interdisciplinary approach. In this sense, I think that NTT laboratories have abundant human resources.

I believe that the phrase "you become good at what you like doing" is an important attitude to have as a researcher. I don't think I have special research talents that are superior to those of others, but I do think I have a stronger interest in cybersecurity issues.

I have seen many people who have stopped doing research despite their very high technical ability or did not take a research job because they said they did not have the confidence to do research. However, research does not produce immediate results; in fact, it can take several years, maybe even 10 or 20 years, to produce a single result.

In such a situation, you may want to quit by thinking that you have no talent; however, if a research theme is something you are interested in, you may be able to continue to work on it with high motivation and interest, regardless of whether it produces results. If you can continue to work on it, the likelihood of achieving results will certainly increase.

For this reason, I first consider whether I really like the research theme I intend to work on. If I really like a research theme, I can only accept the results of my research, whether successful or not, and that those results will not change my liking of the research theme.

—How will you advance your research activities in the future?

R&D on cybersecurity had often considered individual threats in isolation and in a retrospective manner, so it has been difficult to solve fundamental problems. I'd like to see a world in which not only cybersecurity experts but also all engineers have a background in cybersecurity and take cybersecurity into account when manufacturing products. In other words, I want all engineers to share the mindset of a cybersecurity expert. I believe it is my job to help create cybersecurity technology that is available to everyone. In that case, the meaning of the term *cybersecurity expert* would change.

I'm also working on research ethics. In the cybersecurity-research community in Japan, I've been continuously raising awareness of cybersecurity-research ethics since around 2016, and the concept has spread to a certain level (**Photo 1**). In fact, a consultation service on research ethics has been available in Japan since 2018 at the Computer Security Symposium, one of the largest computer security symposiums in Japan, even before measures regarding research ethics were taken at the IEEE (Institute of Electrical and Electronics Engineers) Symposium on Security and

Photo 1. Panel discussion at a symposium in the Japanese cybersecurity community.

Privacy. The Computer Security Research Group of Information Processing Society of Japan has also released a checklist of research ethics in a form that can be used by various research groups.

In 2021, the conduct of a researcher at a US university became controversial. The researcher implemented patches with vulnerabilities to the Linux kernel to evaluate the code review process in the open-source software community and wrote a paper about it. In light of this, a panel discussion was held in the Japanese cybersecurity community to discuss the relationship between cybersecurity researchers and the development community. In this discussion, I argued that (i) experiments on people and their communities and organizations must be designed and conducted with full consideration of their impact on those people, communities, and organizations, (ii) no divisions should exist between the development community and research community, and (iii) it is important for researchers to work together as members of the development community.

It is important that cybersecurity researchers respect software developers and cooperate with them on better technology development on the basis of these three arguments, and I intend to continue to focus my efforts on raising awareness of cybersecurity-research ethics.

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■ **Interviewee profile**

Mitsuaki Akiyama received an M.E. and Ph.D. in information science from Nara Institute of Science and Technology in 2007 and 2013. Since joining NTT in 2007, he has been engaged in research and development on cybersecurity. His research interests include cybersecurity measurement, offensive security, and usable security.

Bandwidth-doubler Technology Eliminates Bandwidth Bottlenecks

Hiroshi Yamazaki
Distinguished Researcher, NTT Device Technology Laboratories

Abstract

In communication systems that involve signal processing using digital circuits, the bandwidth at the interface between digital and analogue is a bottleneck to improving communication speed. We spoke to Distinguished Researcher Hiroshi Yamazaki, who developed the principles of the bandwidth-doubler technology for solving this bottleneck.

Keywords: bandwidth doubler, digital signal processor, analogue multiplexer

Bandwidth-doubler technology for doubling optical communication speed

—What are the ways to increase speed in optical communication?

The speed at which information is transmitted in communication is determined by the product of spectral efficiency and bandwidth.

Spectral efficiency refers to the amount of information that can be transmitted per unit frequency and time. For example, compared with a binary system that represents “0” when the light is off and “1” when the light is on, a quaternary system that represents four values “00,” “01,” “10,” and “11” with four different states of light can transmit information twice as efficiently. Spectral efficiency in optical communication has been dramatically improved in recent years due to performance improvement in digital signal processors (DSPs) and the evolution of algorithms.

Meanwhile, bandwidth refers to the range of available frequencies. The pace of bandwidth expansion, however, has been relatively slow. A particular challenge lies in the analogue bandwidth of the digital-to-analogue converter (DAC) and analogue-to-digital converter (ADC), which convert digital and analogue signals at the input/output unit of the DSP. The DAC and ADC are monolithically integrated with the DSP using complementary metal oxide semiconductor (CMOS) technology. However, while CMOS is almost the only technology in the construction of large-scale digital circuits, it is not necessarily the best technology from an analogue bandwidth perspective. As a result, the bandwidth limitations of DACs and ADCs formed using CMOS technology are becoming a bottleneck in the bandwidth for the entire communication system.

Bandwidth-doubler technology can be used to eliminate this bandwidth bottleneck in order to increase the transmission capacity per transceiver.

—What is the principle of the bandwidth-doubler technology?

Figure 1 shows the principle of the bandwidth-doubler technology. Two DACs (sub-DACs) are

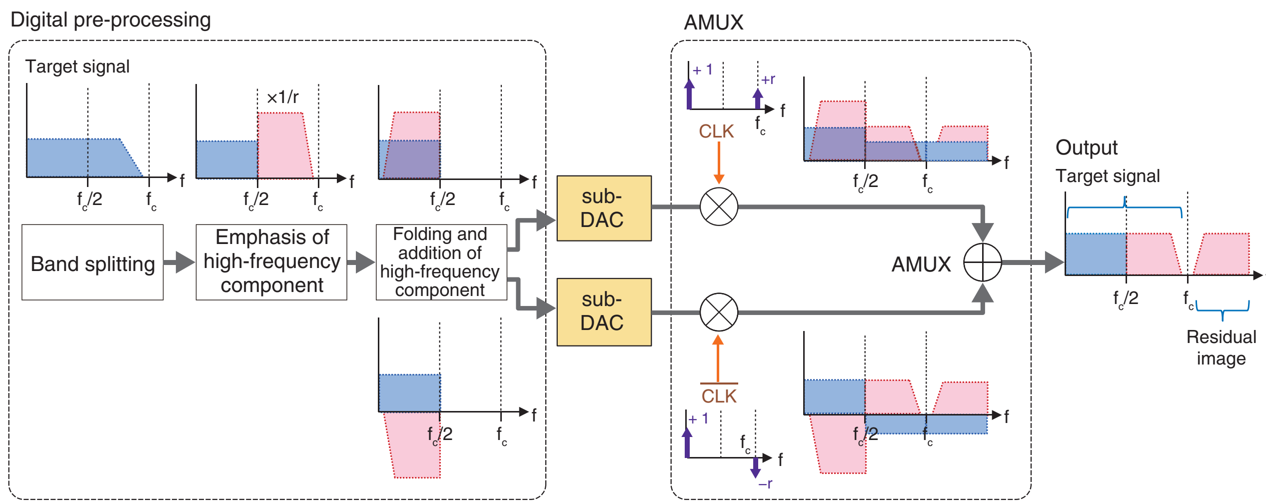

Fig. 1. Principle of bandwidth-doubler technology.

arranged in parallel, and their outputs are multiplexed with an analogue multiplexer (AMUX) to transmit a signal with twice the bandwidth of the signal output by each sub-DAC. Currently, we are focusing mainly on the DAC side (transmitter side), so I will focus my explanation on that.

In the middle of the diagram, the yellow section with two sub-DACs is the bottleneck area. The figure shows many light blue and pink graphs on the right and left of the bottleneck. The "f" on the horizontal axis of the graphs refers to frequency, wherein a wide bandwidth means a wide range extending along the horizontal axis, and a narrow bandwidth means a narrow range along the horizontal axis.

The "target signal" on the left-hand side of the figure is the signal you want to output and has a bandwidth of f_c. However, the sub-DAC only has a bandwidth of $f_c/2$, i.e., half of f_c. In other words, the entire signal cannot be transmitted in its original state, but the signal must not be partly cut off. Therefore, it is necessary to think about how to send the entire target signal through the sub-DAC.

In the bandwidth-doubler technology, digital pre-processing is first carried out in the DSP, where the target signal is separated into low and high frequencies at $f_c/2$ as the threshold. The high-frequency components are then emphasized; these are the pink parts. Two signals are then created, namely, signals with positively and negatively folded high-frequency components. Since these signals have a width of only $f_c/2$, they can pass through the sub-DACs.

The signals then enter the AMUX. The AMUX is a simple electronic circuit in which two input signals are alternately connected to an output at high speed, without distorting the waveform. Switching at a fixed timing is equivalent to making a copy of the input signal (called an image) around the switching frequency f_c on the frequency axis. This widens the bandwidth of the signal. Further, by combining the positive and negative relationship of the above two signals with the positive and negative relationship of the image, the light-blue-colored low-frequency component and the pink-colored high-frequency component reinforce each other in the original frequency domain and cancel each other out in the rest of the frequency domain. This enables the target signal to eventually be transmitted.

The method shown in the figure is the initial version, and we have now validated a method that enables the clock frequency to be halved.

—How is the progress of the research?

Bandwidth-doubler technology was first applied to a relatively simple short-range intensity-modulation direct detection (IMDD) transmission system, where it broke the world record in IMDD optical transmission capacity at 250 Gbit/s per wavelength at that time (2016). Since then, we have widened the device's bandwidth and improved the folding method, increasing the capacity to 400 Gbit/s per wavelength. Also, experiments are underway for digital coherent transmission systems for medium- to long-range applications, and long-distance transmission of high-capacity signals over 1 Tbit/s per wavelength has also been achieved. These results have been published and gained wide attention as top-scoring papers and post-deadline papers by the Optical Fiber Communication Conference (OFC) and the European Conference on Optical Communication (ECOC), the most prestigious academic societies in the field of optical communication.

Various approaches have been proposed in attempts to increase capacity, including by other companies and other organizations. We are also in the midst of competition among the top players.

Investigation of improvements in both device technology and signal processing

—What are the future prospects?

Bandwidth-doubler technology is basically intended for application in optical communication systems. The demand for larger capacities for the devices that make up the optical fiber communication system, especially optical transceivers, is expected to continue in the future. Therefore, we will continue to work on bandwidth expansion technology as one of the approaches to meet these demands. One of our missions is to deploy and promote the innovation of scientifically and academically superior, world-leading technologies, so we will continue our research in this area.

From a technical perspective, there is still room for improvement in the bandwidth doubler, so we are pursuing research both from the device technology and signal processing aspects. For example, developing an implementation technology for compact integration of AMUX and optical modulators is one of the important issues to address. Furthermore, since the idea of bandwidth expansion is not tied to a specific device configuration, we will also aim to develop technologies that enable optical circuits to achieve the same functions as AMUX.

—What led you to the bandwidth-doubler principle?

There were various hints that led to conceiving the bandwidth-doubler principle. I had been conducting research primarily on optical devices until around 2015. In a world where all optical devices were analogue, increasing the capacity of communication entailed various problems. I had also been studying about digital and other technologies, and it was around the time I realized that the improvements in communication capacity in the analogue world would soon reach their limits and high-speed AMUX technology was developed, which led to the idea of the bandwidth doubler, where analogue and digital work together to expand bandwidth.

Although at that time the digital part was outside my specialization, it helped that the environment was in place for easily carrying out various experiments.

—Could you give a message to students, young researchers, and future business partners?

When I talk to researchers from other companies or other institutions at academic conferences, I hear about their problems, e.g., that although they were able to fabricate the device, it is difficult for them to conduct system experiments, and that they do not have access to the devices they want to use for system experiments.

NTT has laboratories that are conducting research across a wide range of fields from devices to systems and that are collaborating in various ways. I think this is a major advantage for us. I am a member of both NTT Device Technology Laboratories and NTT Network Innovation Laboratories. And various achievements have come about, including the bandwidth-doubler technology described above, in collaborations between the two laboratories and with the NTT Device Innovation Center.

I would like to say to students and young researchers that having a different combination of “drawers” from those of other people is an advantage. As a device researcher, I also learned about digital signal processing, which is not my specialization, leading to the development of the bandwidth-doubler technology.

Please do not hesitate simply because it is outside your specialization or because you are a beginner, if it is necessary, take the bold step to learn about the knowledge and technologies in other fields.

■ **Interviewee profile**

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High-output Optical Transmitter and High-sensitivity Optical Receiver for 400-Gbit/s 40-km Fiber-amplifier-less Transmission

Shigeru Kanazawa, Takahiko Shindo, Yasuhiko Nakanishi, Masahiro Nada, Koichi Hadama, Mingchen Chen, Shoko Tatsumi, Atsushi Kanda, and Hirotaka Nakamura

Abstract

We developed a high-output optical transmitter and a high-sensitivity optical receiver for long-distance transmission in the All-Photonics Network that is being promoted under IOWN (the Innovative Optical and Wireless Network). This article introduces the 400-Gbit/s optical transmitter with a semiconductor optical amplifier-assisted extended-reach electro-absorption modulator integrated distributed feedback laser called AXEL, a key device for higher optical output, and the 400-Gbit/s optical receiver with an avalanche photodiode, a key device for higher sensitivity.

Keywords: intensity-modulation direct-detection (IM-DD), AXEL, APD

1. Introduction

The amount of data handled by communication networks has been increasing dramatically with the development of cloud services and other new services, and traffic volume has also been increasing sharply. In response, NTT proposed the Innovative Optical and Wireless Network (IOWN) to increase transmission capacity, decrease latency, reduce power consumption, and provide excellent flexibility in the communication network.

The All-Photonics Network (APN), one of the three main components of IOWN, will introduce photonics technology everywhere, from the network to the terminal and from short distances to long distances, to achieve overwhelmingly lower power consumption, higher quality, greater capacity, and lower latency in network-data transmission.

At the NTT Device Innovation Center, we developed an optical transmitter and optical receiver for intensity modulation format to fabricate a compact and low-power-consumption transceiver and increase transmission capacity. To fabricate the transmitter and receiver for long-distance transmission, a higher output optical transmitter and higher sensitivity optical receiver are needed. We therefore conducted research and development on a semiconductor optical amplifier (SOA)-assisted, extended-reach electro-absorption modulator integrated distributed feedback (EADFB) laser called AXEL [1], which is a key device for high optical output, and an avalanche photodiode (APD) [2], which is a key device for high sensitivity. This work resulted in the development of an optical transmitter and receiver that are capable of transmitting a 400-Gbit/s signal over a distance of 40 km [3, 4]. The developed transmitter and receiver

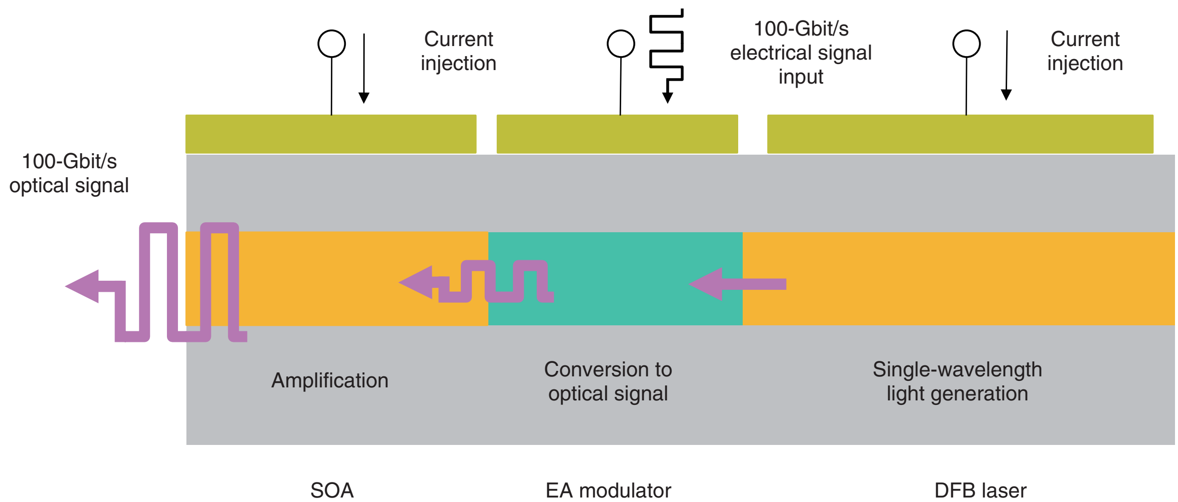


Fig. 1.   Schematic of AXEL chip.

extend the region in which intensity modulation can be applied, contributing to reducing network-interface device size and power consumption.

2. AXEL

The key device of the high-output optical transmitter is a high-speed, high-output optical transmission device, which is generally an EADFB laser that generates an optical signal of 100 Gbit/s per chip. This laser comprises a DFB laser that emits single-wavelength light and an EA modulator that converts an electrical signal to a high-speed, high-quality optical signal. However, conventional EADFB lasers have high optical loss in the EA modulator and inhibit the increase in higher output power.

To address this issue, we have been developing AXEL as a key transmitter that can achieve high-speed optical transmission with high output (**Fig. 1**). An SOA is driven by current injection, and light incident to the SOA is amplified as it propagates. In conventional EADFB lasers, the intensity of the light output by the DFB laser is decreased by modulation in the EA modulator, but in AXEL, the light is amplified by the SOA to obtain a high-output optical signal. The SOA is fabricated from the same semiconductor materials as the DFB laser; therefore small, integrated AXEL chips can be fabricated with the same process, enabling low-cost mass production. Because each SOA chip must amplify a high-speed 100-Gbit/s optical signal, this SOA uses a new optical amplification layer that efficiently converts electrical current into light with less degradation in the optical waveform, thus achieving output of a 100-Gbit/s signal with no loss of quality. The AXEL chip we developed is thus capable of outputting a 100-Gbit/s optical signal with an intensity of +8.0 dBm or more [1]. An optical transmitter that generates a 400-Gbit/s optical signal can be achieved with an array of four discrete AXEL chips.

3. APD

The key device of the high-sensitivity photoreceiver is a high-speed, high-sensitivity PD. The PDs that are generally used in receivers have a theoretical opto-electrical conversion efficiency of 100%, but, in most cases, the actual efficiency is only a few tens of percent because of loss at light incidence and incomplete absorbance of light within the PD.

We developed an APD, a special PD designed to serve as a high-speed, high-sensitivity receiver. A strong electric field is induced within the APD, and more electrons and holes are generated by collisions of ionized photoelectrons in the field. The result is an opto-electrical conversion efficiency that can exceed 100%, enabling the fabrication of a high-sensitivity optical receiver. The main components of the APD are light-absorption layers and an avalanche amplification layer (**Fig. 2**). The optical signal is converted to an electrical signal in the absorption layers, and the resulting electrical signal is amplified in the amplification layer.

The APD converts a 100-Gbit/s optical signal to an

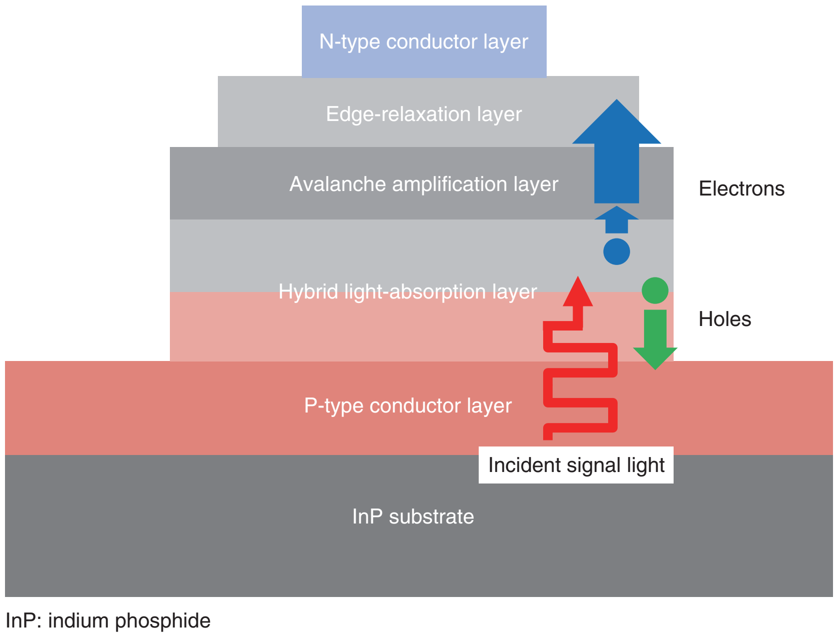


Fig. 2. Schematic of APD chip.

electrical signal. PDs generally must sacrifice sensitivity to received light to achieve higher speed. They also require a waveguide that makes photonic coupling of the incident optical signal to them difficult. For this APD, we adopted a hybrid two-layer light-absorption structure that combines one absorption layer that uses electron diffusion as the main carrier-transport mechanism and another absorption layer that uses hole drift as the main carrier-diffusion mechanism. This makes it possible for the optical receiver to handle a 100-Gbit/s signal while maintaining high sensitivity and facilitating optical coupling with a vertical injection structure [2]. An optical receiver that converts a 400-Gbit/s optical signal to an electrical signal can be fabricated by mounting four APD chips.

4. 400-Gbit/s high-output optical transmitter

Our four-channel, 400-Gbit/s optical transmitter achieves high output power with four AXEL chips that are mounted inside the transmitter on four subassemblies (**Fig. 3(a)**) [3]. Each chip outputs a 100-Gbit/s optical signal. The light wavelengths output from the subassemblies, 1295.5 nm (Lane 0), 1300 nm (Lane 1), 1304.5 nm (Lane 2), and 1309.1 nm (Lane 3), are determined using a local area network-wavelength division multiplexing grid. The output light is collimated after passing through the first lens and input to an optical multiplexer that comprises a mirror, glass block, and wavelength filters. The 400-Gbit/s optical signal from the multiplexer is passed through an isolator and the second lens and then coupled to an internal optical waveguide in a Lucent connector (LC) receptacle. A photograph of the fabricated compact 4-channel optical transmitter is shown in **Fig. 3(b)**. The device is 18.2 mm long, 6.2 mm wide, and 5.4 mm high, small enough to be mounted in a quad small-form-factor pluggable, double density (QSFP-DD) optical transceiver.

We measured the waveform eye diagrams and the output power for operation at 400 Gbit/s. The AXEL chip temperature was 50°C. The laser diode and SOA currents were 80 and 40 mA, respectively. The measured electrical signal was 53.125 Gbaud, and the amplitude voltage of the four-level pulse amplitude modulation signal was 0.75 Vpp. The eye diagrams were observed with a sampling oscilloscope after the signal was passed through a 26.6-GHz low-pass filter and equalization with a transmitter dispersion eye closure quaternary (TDECQ) filter. Clear eye openings were obtained for all lanes, with TDECQ (an indicator of waveform quality) of 2.4 dB or less (**Fig. 4**). Optical output power (optical modulation amplitude (OMA)) of at least +4.7 dBm was also confirmed for all lanes, indicating the high output

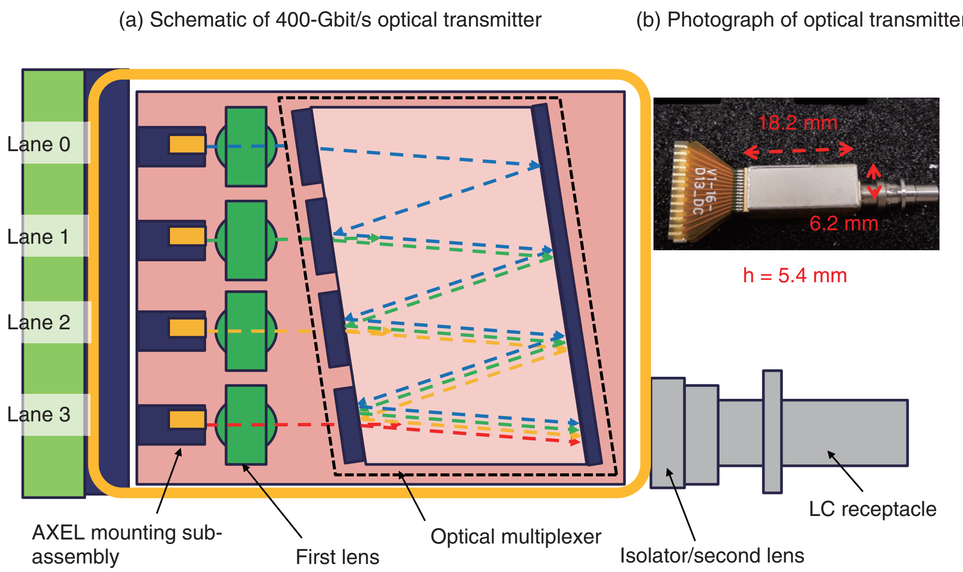


Fig. 3. 400-Gbit/s optical transmitter.

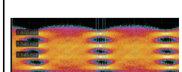
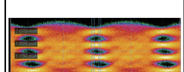
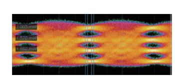
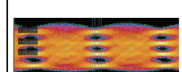
	Lane 0	Lane 1	Lane 2	Lane 3
Eye diagram				
TDECQ (dB)	1.8	2.4	1.2	1.8
Extinction ratio (dB)	3.9	4.2	3.8	4.3
OMA (dBm)	4.7	5.8	5.8	6.3

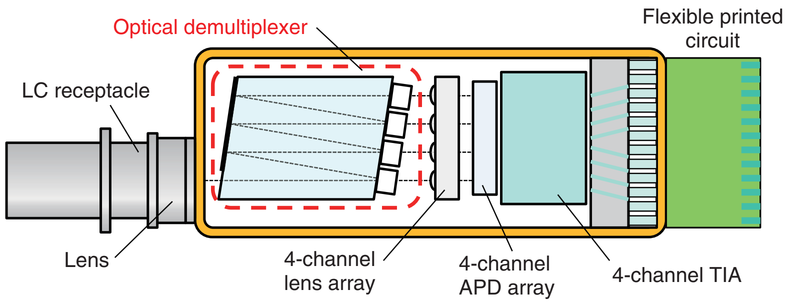
Fig. 4. Eye diagrams for operation at 400 Gbit/s.

characteristic of the AXEL chip.

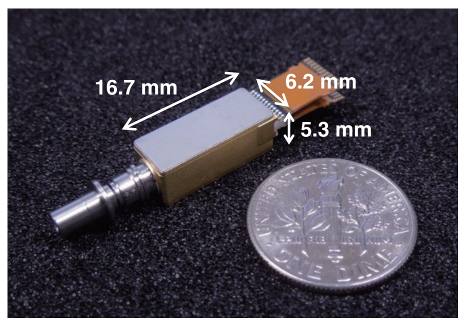
5. 400-Gbit/s high-sensitivity optical receiver

The optical receiver comprises a collimating lens for the light output from the LC receptacle, optical demultiplexer for demultiplexing the four-wavelength optical signal from the transmitter, four-channel lens array, four-channel APD array, and four-channel trans-impedance amplifier (TIA). The optical signal input to the receiver is separated into wavelengths of 1295.5, 1300, 1304.5, and 1309.1 nm by the optical demultiplexer (**Fig. 5(a)**) [4]. The demultiplexed optical signals pass through the lens array and input to the four-channel APD array for conversion to amplified electrical signals. The four 100-Gbit/s electrical signals are output from the receiver via the TIA. A photograph of the fabricated four-channel optical receiver is shown in **Fig. 5(b)**. The device is 16.7 mm long, 6.2 mm wide, and 5.3 mm high, small enough to be mounted in a QSFP-DD optical transceiver in the same manner as the transmitter described above.

We measured the bit-error-rate (BER) of the fabricated four-channel optical receiver with the system configuration illustrated in **Fig. 6**. The four-channel optical transmitter outputs one 100-Gbit/s signal per channel to generate a total signal-transmission rate of 400 Gbit/s. The extinction ratio for the optical signal ranges from 3.8 to 4.3 dB. The signal is input to the four-channel receiver via the variable attenuator, converted to an electrical signal, then output. The output



(a) Schematic of 400-Gbit/s optical receiver



(b) Photograph of optical receiver

Fig. 5. 400-Gbit/s optical receiver.

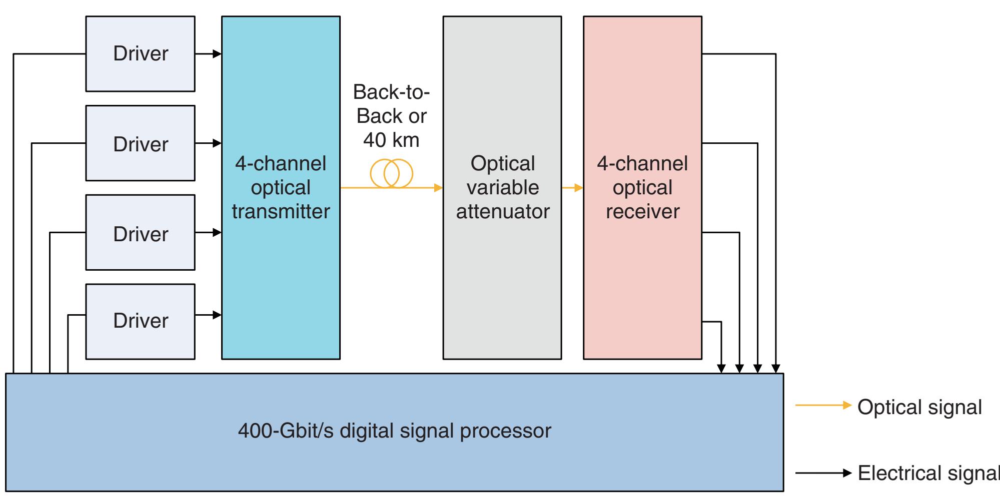


Fig. 6. Evaluation system configuration.

signal is demodulated by the 400-Gbit/s digital signal processor and the BER is calculated under discrete operation.

The BER for each channel is shown in **Fig. 7**. In a back-to-back (BtoB) configuration, where the optical transmitter and optical receiver are connected almost directly, the minimum receiving sensitivity for a BER of 2.4×10^{-4} ranged from –13.5 to –14.0 dBm for

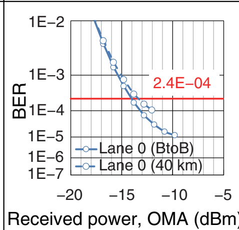
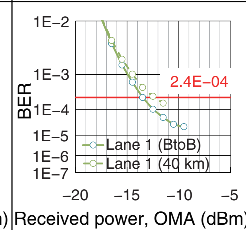
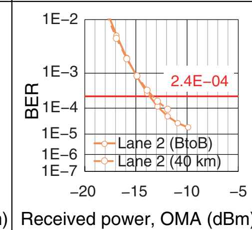
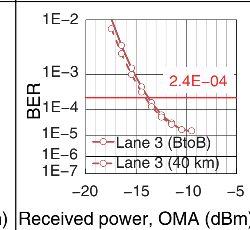
		Lane 0	Lane 1	Lane 2	Lane 3
BER					
Receiver sensitivity (dBm)	BtoB	–14.0	–13.5	–13.7	–13.8
	40 km	–13.4	–12.3	–13.4	–14.1

Fig. 7. BERs for operation at 400 Gbit/s.

OMA. When the receiver was connected to a 40-km standard single-mode fiber as a transmission line, the minimum receiving sensitivity for OMA ranged from –12.3 to –14.1 dBm. These results indicate that the transmission distance in a 400-Gbit/s transmission service can be extended to 40 km by combining a four-channel optical transmitter assembled with AXEL chips and a four-channel optical receiver assembled with APD chips and using intensity modulation.

6. Conclusion

We fabricated a compact high-output four-channel AXEL transmitter and compact high-sensitivity four-channel APD receiver for 400-Gbit/s application. The transmitter and receiver are capable of transmitting a 400-Gbit/s optical signal to a distance of 40 km over optical fiber by intensity modulation, with the expectation of a reduction in power consumption. These indicate that the fabricated AXEL transmitter and APD receiver are promising technology for high-capacity and energy-efficient networks.

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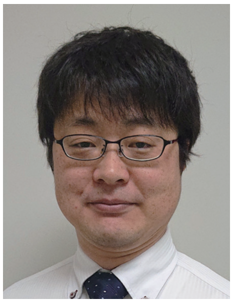

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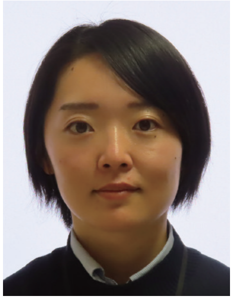

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C+L-band Colorless, Directionless, Contentionless Reconfigurable Optical Add/Drop Multiplexing for High-capacity Network Flexibility

Kenya Suzuki, Koichi Hadama, Shuto Yamamoto, Hiroki Taniguchi, and Yoshiaki Kisaka

Abstract

We investigated the possibility of expanding the operating wavelength range of one of the most flexible optical networks, i.e., colorless, directionless, contentionless reconfigurable optical add/drop multiplexing (CDC-ROADM), to the C+L-band. By expanding the operating wavelength range of multicast switches, which are indispensable for CDC-ROADM, to the two bands of C+L, a seamless optical node can be achieved. This concept reduces the complexity in network equipment as well as network operation because it enables operation without operators having to be aware of the bands.

Keywords: C+L-band optical network node, C+L-band multicast switch, CDC-ROADM (colorless, directionless, contentionless reconfigurable optical add/drop multiplexing)

1. Introduction

The All-Photonics Network (APN), one of the three technologies that comprise the Innovative Optical and Wireless Network (IOWN), is expected to leverage photonics technology to achieve a significant increase in the potential of the information-processing infrastructure, something that is difficult to achieve with current electronics technology [1]. The APN is expected to achieve a 125-fold increase in transmission capacity and maximum end-to-end adoption of optical technology from the network to the terminal. For high-capacity optical transmission, it is important to expand the use of wavelength-division multiplexing (WDM), which is currently used in optical networks, in addition to the application of technologies that have not yet been commercialized such as spatial multiplexing. In other words, the wavelength bandwidth used for optical fiber communications will be expanded to achieve higher capacity. Expanding the wavelength bandwidth of WDM is also effective in the end-to-end application of optical technology [2], which requires an increase in the number of optical paths that can be established. In this case, the expansion of the wavelength bandwidth in WDM is also an important issue.

2. Multiband ROADM network

In optical networks, optical switches are essential for routing light as it is. Reconfigurable optical add/drop multiplexing (ROADM) systems have been introduced for optical networks using optical switches, which enable optical signals to be added and dropped at each node. By enabling optical-signal transmission between multiple rings without electrical regeneration, ROADM systems can flexibly reconfigure the network and reduce operation and maintenance costs. The conventional single-ring network has been extended to a more economical multi-ring network, as shown in **Fig. 1** [3]. The optical-node configuration called colorless, directionless, contentionless

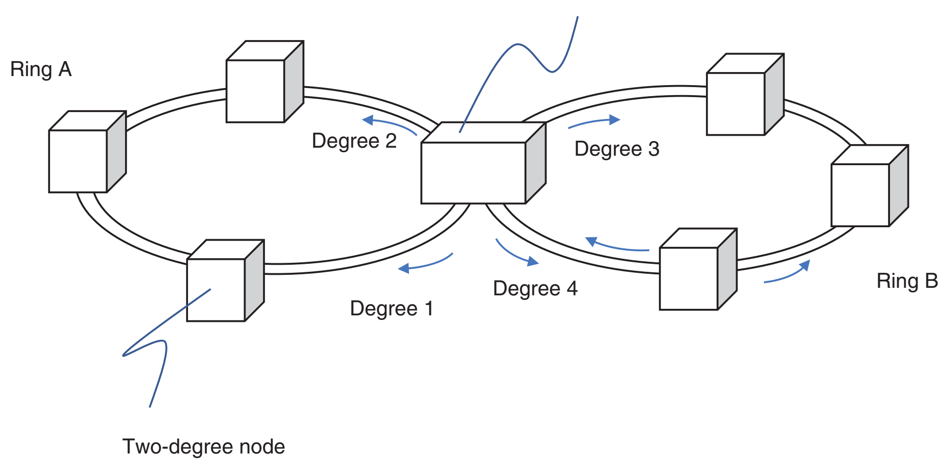


Fig. 1. Example of multi-ring network.

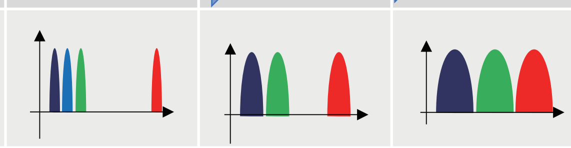
Bit rate	100 Gbit/s	500 Gbit/s class	1 Tbit/s class
Baud rate	32 Gbaud	64 Gbaud	130 Gbaud
Channel spacing	50 GHz	>75 GHz	>150 GHz
Channel count per band	~90	× 2/3 ~60	× 1/2 ~32
Signal spectrum			

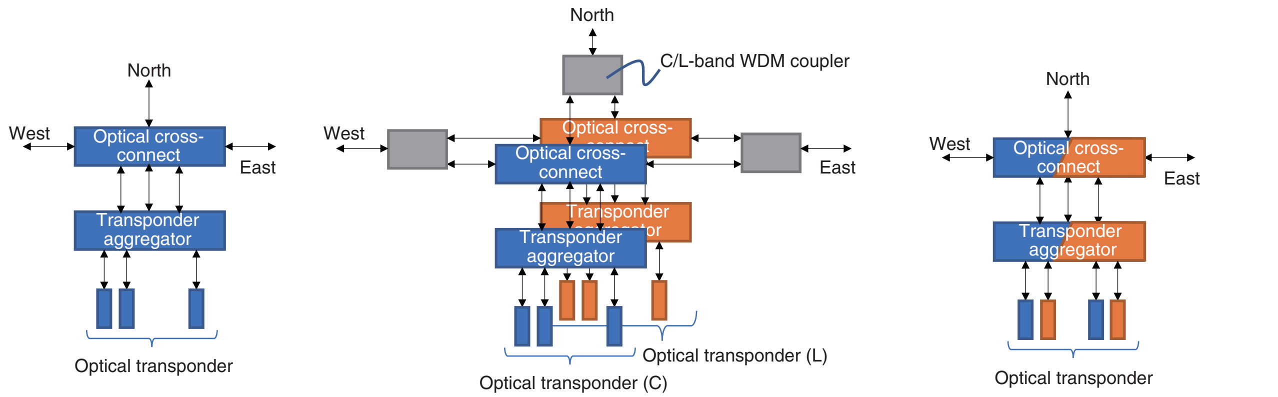
Fig. 2. Relationship between signal baud rate and channel count per band.

(CDC)-ROADM is one of the most flexible optical-node configurations for efficient data communication in multi-ring and mesh networks. It is not only effective for efficient operation of communication resources [4] but also expected to contribute to rapid restoration in the event of optical-transmission-line breakdown during a disaster [5].

Another trend in optical transmission technology is the discussion about increasing the baud rate of optical signals [6]. High baud rates are suitable for transmitting large signals over long distances. This is because a high-baud-rate signal contributes to a reduction in the level of multiplicity when compared with a signal of the same bit rate, thus expected to improve the signal-to-noise ratio. However, high-baud-rate signals occupy a wider signal bandwidth, which reduces the number of wavelengths available in a single-band ROADM system. As shown in **Fig. 2**, for example, a 100-Gbit/s signal occupies about 32 GHz, and about 90 wavelength channels can be deployed in the currently used C-band (1530 to 1565 nm) or L-band (1565 to 1625 nm) [7]. For a 500-Gbit/s-class signal with an occupied bandwidth of 64 GHz or 1 Tbit/s-class signal with an occupied bandwidth of 130 GHz, only about 60 or 30 waves can be placed at most, respectively. The use of both C- and L-bands is an effective solution to this problem.

3. C+L-band CDC-ROADM

CDC-ROADM is an optical network node configuration that makes one of the most efficient use of the optical transmitters and receivers (transponders) installed in a system. Because an optical node must



(a) Single-band CDC-ROADM node

(b) Multiband CDC-ROADM node with conventional switch devices for single band

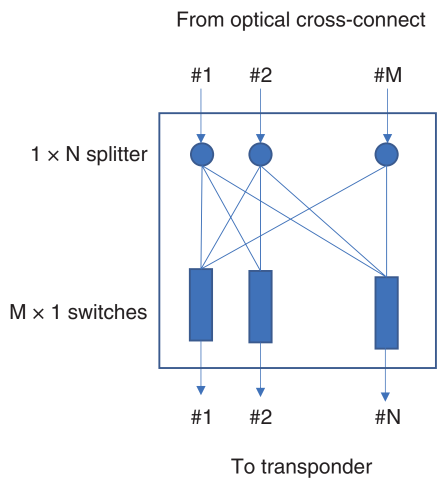
(c) Multiband CDC-ROADM node with C+L-band optical cross-connect and multicast switches

Fig. 3. Configuration of multiband CDC-ROADM node.

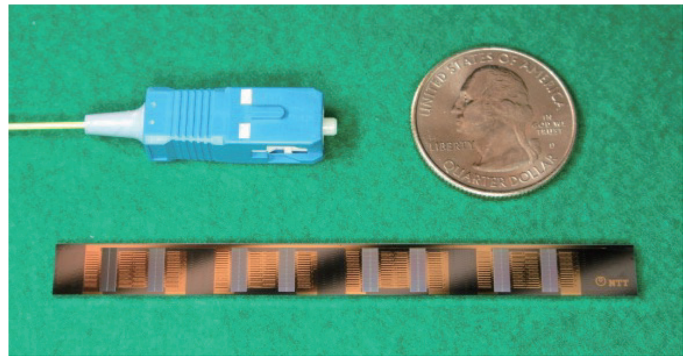
be able to communicate with optical nodes in other directions, a CDC-ROADM node can use optical transponders installed in the node for communication with any direction with the fewest restrictions, thus effectively using communication resources. **Figure 3(a)** shows a typical CDC-ROADM configuration, which consists of an optical cross-connect block and optical transponder aggregation blocks. The optical cross-connect switches optical signals from different nodes directly to other paths (e.g., from West to East) or uses these signals for communication between the node and others. The optical transponder aggregator controls the connection between the optical cross-connect and optical transponder for the optical signals handled by the node. In conventional ROADM systems, optical transponders can only be used for communication with a specific direction (directioned), or only one optical transponder of the same wavelength can be used (contensioned). CDC-ROADM is a highly flexible optical node configuration that enables any optical transponder to be used for communication with any path as long as that path's wavelength is not already in use. The NTT Device Innovation Center was the first in the world to successfully implement multicast switches [8].

With the shift to multiband optical transmission, CDC-ROADM, which has been configured with a single C- or L-band, must now also be multiband. If a CDC-ROADM is configured using conventional optical switch devices that operate only in the C- or L-band, it will have a complex configuration, as shown in **Fig. 3(b)**. Both the optical transponder aggregator and optical cross-connect must be prepared for the C-band and L-band, and the optical signals handled by each must be combined and divided by a C-/L-band (de)multiplexer to communicate with the transmission fiber, doubling the amount of equipment compared with the conventional single-band system. This results in complexity in the node configuration as well as operation because operators have to be aware of the bands. For example, optical transponders are optimized for only the C- or L-band, so that the operator needs to be careful into which system he/she should plug the transponders. In contrast, by using a multicast switch with an extended operating wavelength range to the C+L-band, a CDC-ROADM node with a simple configuration can be implemented, as shown in **Fig. 3(c)**. This is thought to contribute to the reduction in errors during operation.

Multicast switches have intrinsic loss due to their principle. **Figure 4(a)** shows the circuit topology of a multicast switch that accommodates M-degree × N transponder ports. The arrow indicates the direction of optical-signal propagation where the figure shows the case of signal drop use. **Figure 4(b)** shows the appearance of the optical circuit chip of the fabricated C+L-band multicast switch. The multicast switch contains a splitter that splits the input signal into N branches. This is the principal loss factor and cannot be avoided. Therefore, it is preferable to reduce the number of branches as much as possible for optical transmission characteristics, but reducing the number



(a) Configuration of multicast switch



(b) Appearance of C+L-band multicast switch

Fig. 4. Multicast switch.

Table 1. Dependence of add/drop ratio on the number of branches of multicast switch and signal baud rate.

	Number of transponder ports of multicast switch				
	4	8	12	16	24
Single-band node with 32-Gbaud signals	6.8%	13.5%	20.3%	27.1%	40.6%
C+L-band node with 130-Gbaud signals	13.0%	26.0%	39.1%	52.1%	78.1%

of branches also impacts the achievable add-drop ratio. However, when dealing with high-baud-rate transmission, the add-drop ratio can be kept at the same level as the conventional single-band version of the node even if the number of branches is reduced. In a high-baud-rate system, such as 130 Gbaud, the number of wavelengths that can be allocated in a band is also reduced, as mentioned above. Therefore, the reduction in the add-drop ratio due to the reduced number of branches can be maintained at the same level compared with a conventional 32-Gbaud system. **Table 1** summarizes the add-drop ratio for a single-band system with a conventional 32-Gbaud signal and a C+L-band configuration of 130-Gbaud signals. The former is assumed to have a channel spacing of 50 GHz and 96 signals in the C-band, while the latter has a spacing of 150 GHz and 64 signals in both the C- and L-bands. The add-drop ratio depends on the size of the wavelength selective switch (WSS) in the optical cross-connect block. In this article, we assume a 1 × 20 WSS, which was available when the single-band system was developed, for the conventional single-band-only system, and 1 × 32 WSS, which has been put into practical use, for the C+L-band ROADM system. As shown in Table 1, a C-band-only system using a multicast switch with 8-degree ports and 16 transponder ports has an add-drop ratio of 27%, while a multicast switch with 8 optical transponder ports has an add-drop ratio of 26% and can be obtained for a 130-Gbaud signal. Therefore, even if the number of multicast-switch branches is halved from 16 to 8, the same level of operability can be secured as with the conventional single-band configuration. In practice, it is reasonable to estimate the required average add-drop ratio by dividing the total number of wavelengths by the number of nodes in the ROADM system. Thus, even a network with 10 or so nodes requires an average add-drop ratio of only 10%. The cases shown in Table 1 clearly satisfy this requirement.

4. Summary

We described the feasibility of a CDC-ROADM configuration with an optical transponder aggregator that operates in the C+L-band. We also successfully conducted feasibility verification experiments of a C+L-band CDC-ROADM node using the aforementioned C+L-band multicast switch [9].

Multiband technology not only increases capacity but also increases the degree of freedom in ROADM systems by expanding the number of transmission channels. Combined with the increase in transmission distance due to higher baud rates, multiband technology contributes to the advancement of optical networks. NTT is currently conducting research and development of the APN for IOWN. To implement the APN, we will continue our research and development to dramatically expand the transmission capacity and improve optical transmission systems by increasing the speed to 1 Tbit/s by using a wider wavelength band such as the S-band as well as using spatial multiplexing technology.

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Development of Membrane Optical Modulators for IOWN

Tatsurou Hiraki, Takuma Aihara, Takuro Fujii, Koji Takeda, Toru Segawa, and Shinji Matsuo

Abstract

To develop a high-speed, large-capacity optical network with low power consumption, which is important for IOWN (the Innovative Optical and Wireless Network), we are conducting research and development on membrane optical devices that integrate III-V compound semiconductors on silicon-photonics circuits. Membrane optical devices are expected to be used for high-modulation efficient lasers and optical modulators because they can achieve high optical confinement in the core layer. This article introduces the current state of research and development focusing on optical modulators and the integration of such modulators and lasers on the basis of membrane-device technologies.

Keywords: silicon photonics, optical interconnection, optical modulator

1. Introduction

Optical interconnection is a technology that is more advantageous than data communication using electricity as the transmission capacity and transmission distance increase due to the characteristics of wide band and low loss of optical fiber. This technology has been used in long-distance communication networks since the 1980s. Due to the increase in Internet traffic, the application area where optical fiber can show its superiority has been expanded to shorter-distance transmission, and optical interconnection is widely used in datacenter networks. As the number of devices connected to the Internet and the amount of traffic from devices increase, it is expected that the increase in traffic will continue. Therefore, research interests are to increase the transmission capacity where optical interconnections have already been applied and apply optical interconnection to shorter-distance transmission, as shown in **Fig. 1**. Specifically, optical interconnections inside the board and chip are expected to become important for improving the throughput of electronic devices such as routers and servers.

For this purpose, it is important to reduce the power consumption and cost of optical transmitters. To reduce power consumption, it is important to modulate optical devices at high speed. To achieve this, it is necessary to increase the optical-confinement factor in the core region as much as possible. A large cost is required for assembly and testing, so cost reduction is necessary by integrating multiple optical devices in the same substrate. It is therefore important to use silicon (Si) photonics technology, which can be used to fabricate optical waveguides with low loss and optical circuits with high performance by using fabrication technology used in Si electronic circuits. Since it is not possible to fabricate a laser or a highly efficient optical modulator using Si, a method for integrating III-V compound semiconductors, which are the materials for lasers and modulators, is an issue for large-scale integration.

In this article, we describe membrane optical devices on Si substrates. Such devices are thin-film optical devices fabricated on low-refractive materials. We previously fabricated and demonstrated high-efficiency lasers and modulators using indium phosphide (InP)-based compound semiconductors with a typical thickness of about 250 nm on silicon dioxide (SiO_2)/Si substrates [1–5]. High optical confinement of the core layer can be obtained by sandwiching a device between low-refractive index materials such as SiO_2

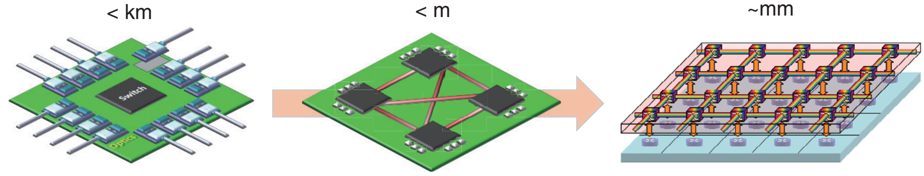


Fig. 1. Development of optical interconnection.

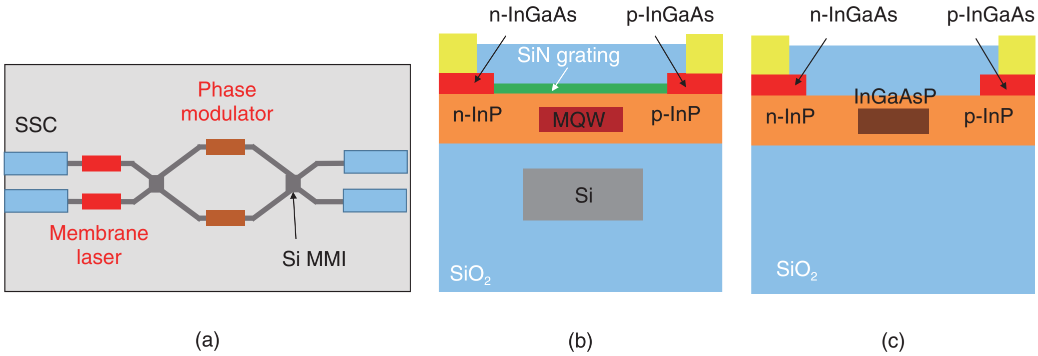
and air. We specifically describe the optical modulators in detail.

2. Membrane optical modulators

Optical modulators can be classified into two types: phase modulators that mainly modulate the refractive index and intensity modulators that modulate the absorption coefficient. A phase modulator is used as a Mach-Zehnder (MZ) modulator in combination with an MZ interferometer, and by combining MZ modulators and modulating the phase and intensity, it is possible to obtain a large-capacity transmission exceeding 1 Tbit/s per wavelength and long-distance transmission. Typical materials used are lithium niobate ($LiNbO_3$), Si, and InP. Due to the increase in traffic, optical interconnects increase their importance in a datacenter. Thus, it is important to reduce the transmitter cost by reducing the device size and integrating many devices including lasers on the same chip. For this purpose, InP-based and germanium silicon (GeSi) intensity modulators, which are one order of magnitude more efficient than $LiNbO_3$ and Si, are considered key devices. Since intensity modulators use only the intensity change as a signal, the transmission capacity is generally smaller than that of MZ modulators, but their simple and compact configuration is important when a large number of transmitters are required at shorter distances. Considering their use in the 1.3-µm wavelength used in datacenters, there is currently a problem in the growth of GeSi; thus, InP compound semiconductors have become advantageous in addition to integrate lasers.

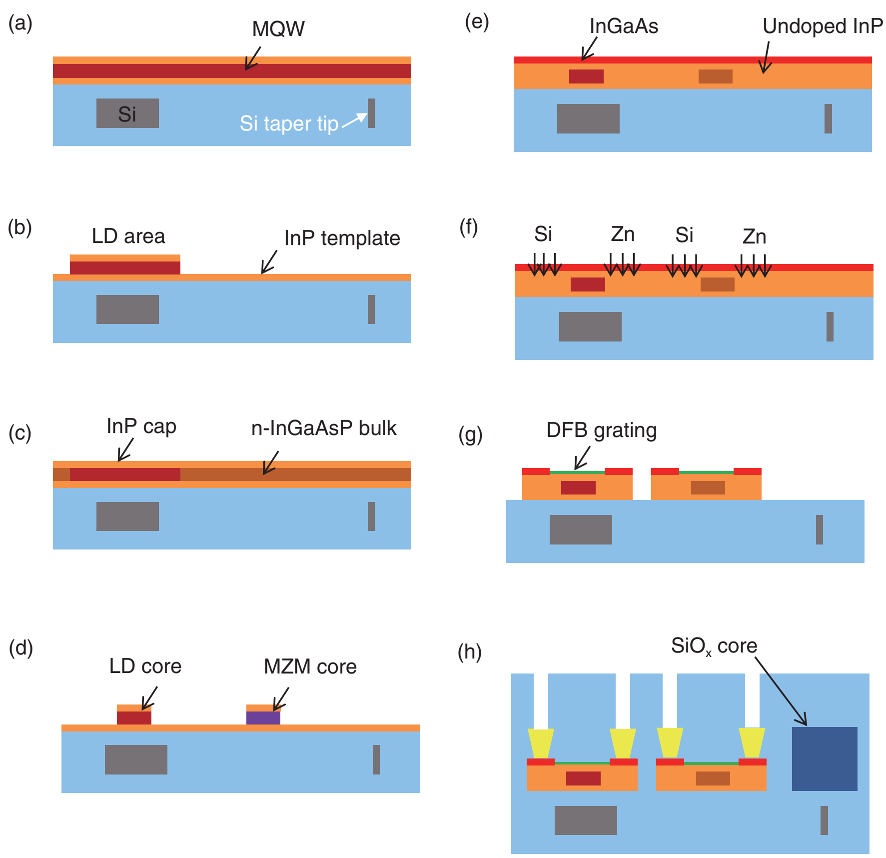
Figure 2(a) shows a schematic of a photonic-integrated circuit using an MZ modulator consisting of a Si MZ interferometer and InP phase modulators, and membrane lasers [6]. By integrating the spot size converters (SSCs), it is possible to assemble a device with optical fiber with low-coupling loss by butt-coupling the device to the optical fiber without using a lens. **Figures 2(b)** and **(c)** show the cross-sectional view of a membrane laser and membrane phase modulator. Reduction in the optical-confinement factor in the laser core layer is important to suppress internal loss and spatial hole-burning because the laser for biasing the modulator requires high output power and stable single-mode lasing. Therefore, the Si waveguide is placed under the laser core layer. Since the effective refractive index of the membrane-laser structure is similar to that of the Si waveguide, the optical-confinement factor in the laser core layer can be controlled by adjusting the width of the Si waveguide. In a phase modulator, the Si waveguide is eliminated to maximize the optical-confinement factor. Therefore, the membrane optical device can freely design the confinement of light between the Si waveguide and membrane optical device.

The fabrication process is shown in **Fig. 3**. (a) A Si waveguide is fabricated using a Si on insulator (SOI) substrate, and after the entire waveguide is covered with SiO_2, it is planarized using chemical mechanical polishing, and the multiple-quantum-well (MQW) layer, which is the core layer of the laser grown on the InP substrate, is directly bonded on the planarized SiO_2. (b) The MQW layer is removed by selective etching except for the area that includes the laser core layer, and the InP layer is exposed. (c) An n-type indium gallium arsenide phosphide (InGaAsP) layer, which is the core layer of the phase modulator, is grown on the InP layer by using metal organic chemical vapor deposition. (d) The laser and phase modulator core regions are formed using selective etching. (e) Core regions are embedded with an undoped InP layer by using selective regrowth. (f) Selective doping is carried out to form n- and p-type doping regions. (g) The laser and phase modulator are separated and a grating is formed in the top surface layer of the laser region. (h) Finally, an SSC and electrodes are formed. The advantage of this fabrication method involves the regrowth of compound semiconductors



InGaAs: indium gallium arsenide
MMI: multimode interferometer
SiN: silicon nitride

Fig. 2. (a) Schematic diagram of photonic integrated circuit including MZ modulator and membrane laser. (b) Cross-sectional view of membrane laser. (c) Cross-sectional view of phase modulator.



DFB: distributed feedback
LD: laser diode
Zn: zinc

Fig. 3. Fabrication procedure.

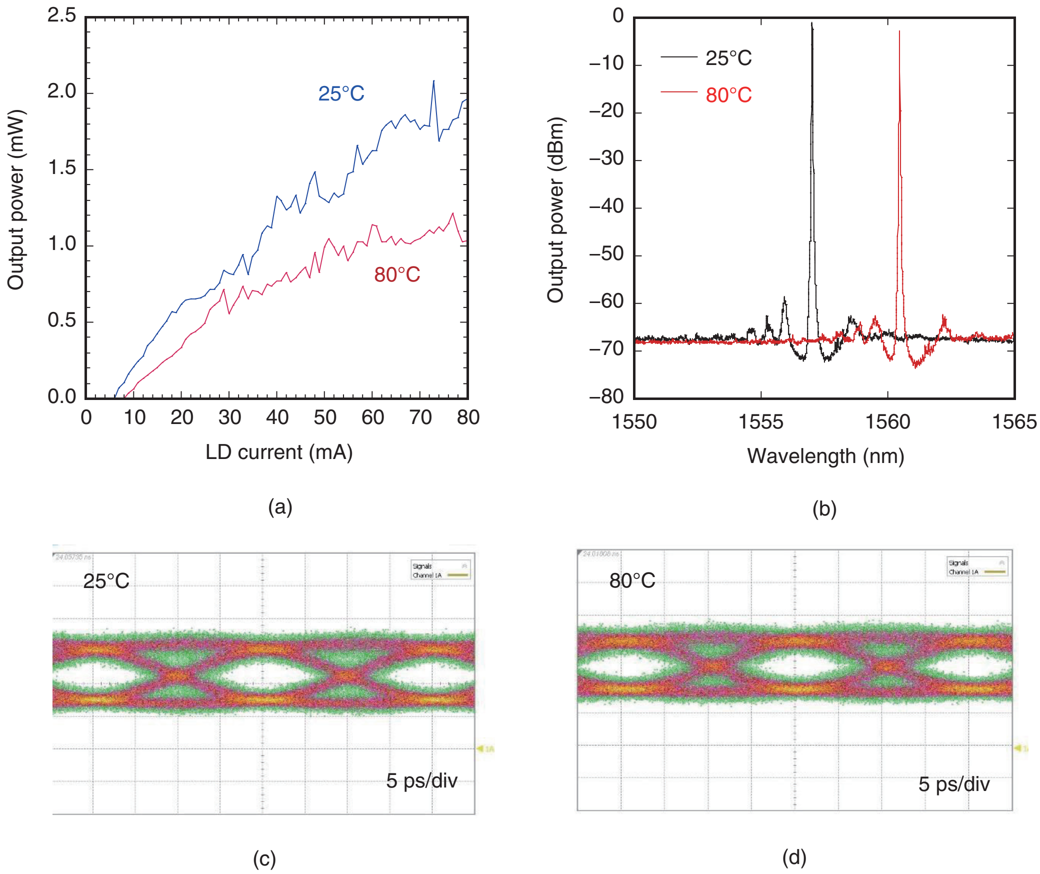
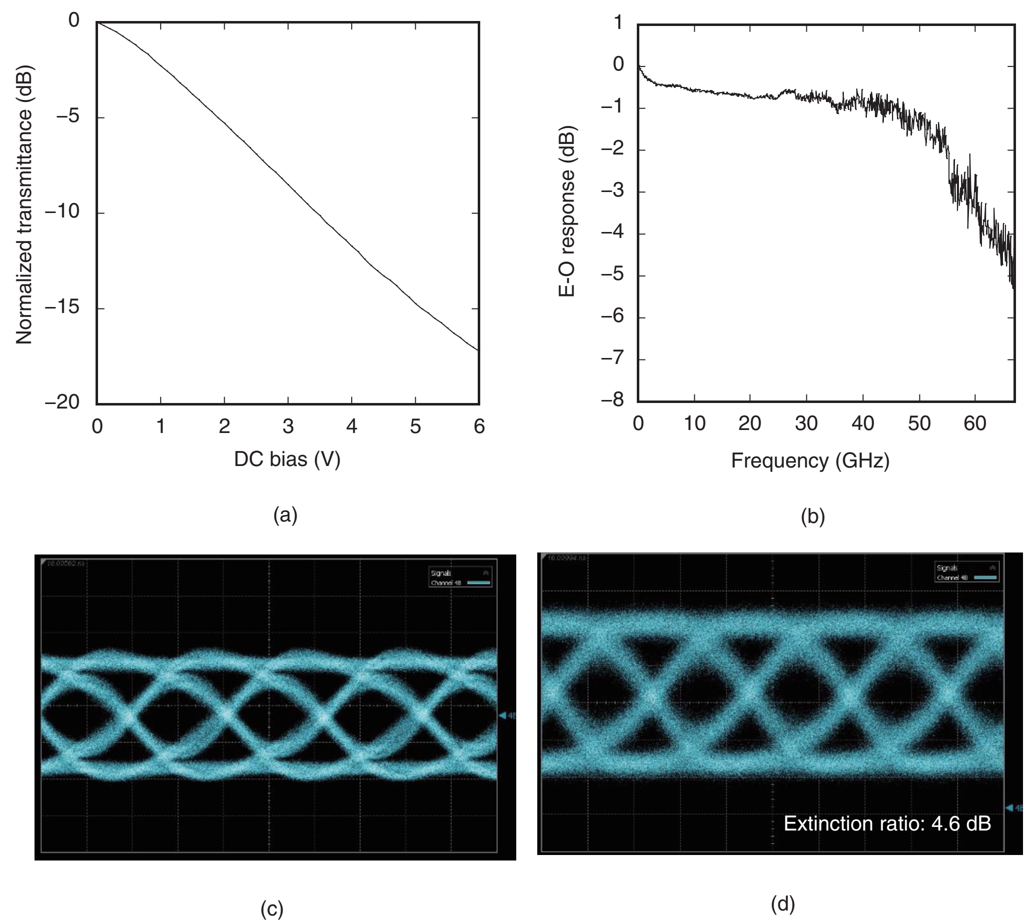


Fig. 4. Characteristics of fabricated device. (a) I-L characteristics at 25 and 80°C. (b) Lasing spectra. (c), (d) Eye diagrams with 50-Gbit/s NRZ signals at 25 and 80°C.

on Si substrates. Since the total thickness of the membrane optical device is about 230 nm, regrowth on the Si substrate becomes possible due to the resistance to the strain caused by the thermal-expansion coefficient difference between Si and InP. Thus, InP-based semiconductors with different bandgaps, such as laser-active layers and phase-modulator layers, can be fabricated on Si on a wafer scale. Since the marker for the stepper on the Si substrate is used for the alignment of the III-V core regions, the Si waveguide and membrane optical device can be integrated with the alignment accuracy of the stepper.

The characteristics of the fabricated device are shown in **Fig. 4**. The length of the laser-active region and phase modulator is 500 μm. Thanks to the high modulation efficiency of the n-InGaAsP layer, the length of the phase modulator is much shorter than the Si phase modulator, which has a length of several millimeters. Figure 4(a) shows the current dependence of the output light intensity when the MZ optical modulator is set to the OFF state. The output light is received by the lensed fiber at measurement temperatures of 25 and 80°C. In this experiment, reflection occurred at the end facet of the device, resulting in mode hopping, as shown in the figure. It is possible to suppress the reflection by directly connecting fibers, but we use lensed fiber to simplify the experiment. The threshold current was about 6 mA at 25°C and about 8 mA at 80°C. The maximum fiber output power was 2 mW at 25°C and about 1 mW at 80°C. The fiber coupling loss was 3 dB. Figure 4(b) shows the oscillation spectra at 25 and 80°C with bias currents of 76.0 and 50.6 mA, respectively. Single-mode oscillation was obtained, and the side mode suppression ratio at 80°C was 59 dB. Figure 4(c) shows the dynamic characteristics of the MZ modulator when modulated with a 50-Gbit/s non-return-to-zero (NRZ) signal at operating temperatures of 25 and 80°C. An electrical signal with a peak voltage of 2.5 V was input into the phase modulator, and the signal



DC: direct current
E-O response: electro-optical response

Fig. 5. Characteristics of fabricated EAM. (a) Voltage dependence of transmittance at operating wavelength of 1280 nm. (b) Small signal response at bias current of 2 V. (c) Input electrical and (d) output optical eye diagrams with 100-Gbit/s NRZ signals.

was terminated by 50 ohms. Although the extinction ratio was as low as 3 dB, we confirmed a clear eye-opening at both temperatures. The extinction ratio can be improved by differential operation and applying an inverted signal to the other electrode of the phase modulator. The core layer of the phase modulator is relatively long (500 µm) for lumped electrodes, but it can operate on 50-Gbit/s NRZ signals thanks to the low capacitance of the membrane structure.

We also developed an electro-absorption modulator (EAM) using InP-based MQWs [7]. Since we can obtain large absorption change in the EAM, there is no need to use an interferometer such as an MZ modulator, which results in a very simple configuration. Therefore, EAMs with a core-layer length of about less than 300 µm on InP substrates are integrated with lasers and are widely used in datacenters. However, the operation speed of the EAM on InP substrate is limited by the capacitance, and it is necessary to use the 50-ohm termination and apply the traveling wave-type electrode to increase the speed. Therefore, the EAM using a membrane structure has attracted attention due to its low capacitance. Since it is important to increase the optical-confinement factor to the core layer as well as the phase modulator, we fabricated a device without placing a Si waveguide under the EAM core layer. A nine-layer MQW with a photoluminescence peak of 1230 nm was used as the core layer. The voltage dependence of transmittance at an operating wavelength of 1280 nm is shown in **Fig. 5(a)**. For a device with a core-layer length of 200 µm, an extinction ratio of 8.5 dB can be obtained by changing the bias voltage from 0 to 3 V. The insertion loss of the EAM excluding the fiber coupling loss is estimated to be 3 dB compared with a Si waveguide. **Figure 5(b)** shows the small-signal response. The operating wavelength was set to 1280 nm, and the bias voltage was set to 2 V. We did not use a 50-ohm termination. As shown in the figure, the 3-dB band was 59 GHz. This clearly shows the advantage of a membrane photonic device.

Next, we measured the eye diagrams of the 100-Gbit/s NRZ signal. **Figures 5(c)** and **(d)** show the input electrical signal and optical output signal, respectively. The bias voltage of the EAM was set to 1.2 V. An electrical signal with a peak voltage of 0.12 V from the pulse pattern generator was amplified with an electrical linear amplifier of 22 dB and applied to the EAM. The eye diagram is comparable to the input electrical signal, and the extinction ratio was 4.6 dB. Since laser integration is possible with the same manufacturing process as a MZ-modulator-integrated distributed feedback laser, it is expected to be applied to the optical interconnection of short distances such as inside racks and boards.

3. Summary

This article argued that membrane optical modulators are suitable for fabricating modulators with high speed and low power consumption because of their high optical-confinement factor and low capacitance. An SSC is also integrated so that it can be easily connected to fiber arrays. Because an SCC can be integrated on the Si photonic circuit, it is also possible to integrate it with multiplexer/demultiplexer components using the Si waveguide. Therefore, it is expected to be a key device for short-distance optical interconnections, where it is important to integrate optical devices at high density and maximize throughput per unit length.

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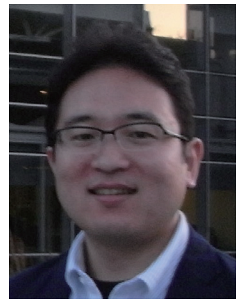

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Observation of Exceptional Point Degeneracy with Current-injected Photonic Crystal Lasers

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Abstract

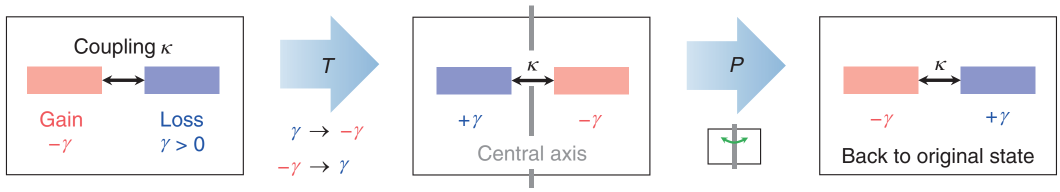
Coupled resonators and coupled waveguides with contrast of their gain and loss are non-Hermitian optical systems, which are based on energy-non-conserving processes. They have been reported to exhibit a number of unconventional phenomena that are expected to contribute to practical applications. We developed a coupled system of two current-injected photonic crystal lasers that enable precise control of gain and loss, thus establishing a promising non-Hermitian nanophotonic platform. We introduce our demonstration of a peculiar non-Hermitian mode degeneracy called an *exceptional point* (EP) and the EP-based enhancement of spontaneous emission with this system.

Keywords: non-Hermitian photonics, exceptional point, photonic crystal lasers

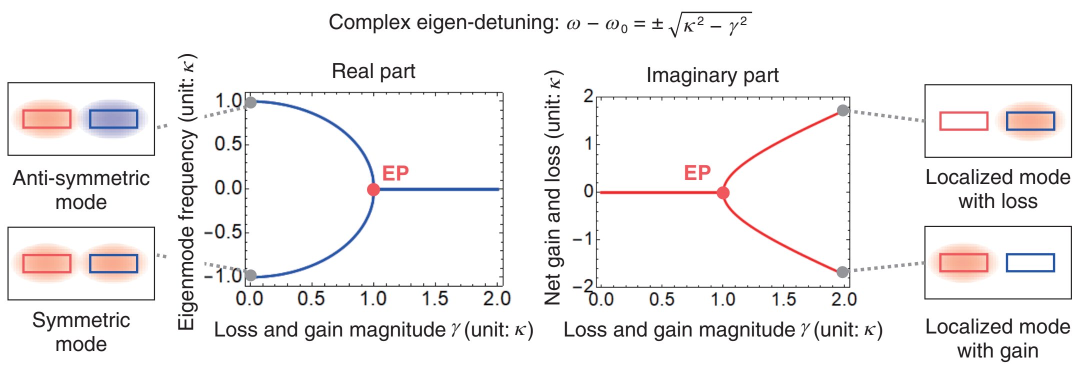
1. Non-Hermitian photonics

To generate and control optical signals, devices such as lasers, modulators, and photodetectors are required. They vary the intensity of light by amplifying it via stimulated emission, releasing it from optical signal channels, or absorbing it with the generation of electric carriers. In the Maxwell equation of electromagnetism, optical amplification gain and absorption loss in a medium are expressed as the imaginary part of its refractive index. When resonators and waveguides comprise media with finite imaginary parts of refractive indices, possible states of electromagnetic waves confined in them (eigenmodes) have generally complex frequencies and propagation constants (eigenvalues). The imaginary part of the eigenvalue corresponds to the rate of optical gain or loss per unit time for a resonator and per unit propagation distance for a waveguide.

A system is called Hermitian when the energy of the physical quantity of interest (light waves here) is conserved. In contrast, a system based on energy-non-conserving processes is *non-Hermitian*. Since the mode eigenvalues of a non-Hermitian optical system are complex numbers, as mentioned above, light waves there may continue to be amplified or absorbed until the carrier response is saturated or may be totally radiated out. Unlike Hermitian systems, eigenmodes of non-Hermitian systems are generally not orthogonal to each other. Given that it is impossible to measure a completely closed system without energy dissipation, all the states we observe are those of non-Hermitian systems. This means that every state of optical systems may not be independent but more or less mixed with other ones. Responses of such non-Hermitian systems seem to be much more diverse and difficult to understand compared with Hermitian systems that are assumed as approximations in many cases. In addition, gain and loss had been considered to only control the intensity of light in photonics. Thus, the research for other applications of them had been limited.



(a) PT symmetry of a system of two coupled cavities. κ: coupling rate.
γ: loss rate in a single cavity mode (a negative value represents gain).



(b) EP transition of the eigenmode frequency and net gain and loss. The red and blue ellipses in the mode schematics represent antiphase fields. ω_0: resonance frequency of each cavity mode.

Fig. 1. PT symmetry and EP phase transition of two coupled resonators.

1.1 PT symmetry

A turning point in these circumstances was the introduction of the concept of parity-time (PT) symmetry to photonics [1] by the group headed by Professor Christodoulides at the University of Central Florida. Parity in PT symmetry means spatial inversion. This corresponds to setting a central axis or plane of symmetry (double-sided mirror) in space then inverting the system (or jumping to the world on the other side of the mirror). Time in PT symmetry stands for time reversal, which means turning gain to loss and loss to gain. A system is said to have PT symmetry when both of these operations make it get back to its original shape. While PT symmetry has attracted attention in quantum mechanics, Makris et al. showed that the analogy of PT symmetry in the above-mentioned sense held in the refractive index distributions of optical systems. They also showed that such a system could have a peculiar mode degeneracy called an exceptional point (EP).

We now explain the characteristics of a coupled two-cavity system with PT symmetry shown in **Fig. 1(a)**. We assume that each resonator has an eigenmode (cavity mode) with an identical resonance frequency when isolated. The cavities are placed in proximity with an interval of the order of the mode wavelength. Thus, a small number of fields of one cavity mode seeps into the other via the evanescent wave[*1] so that they are coupled with each other. The system is PT-symmetric when two cavities have loss and gain with the same magnitude γ. Note that the gain rate is denoted as a negative value of $-\gamma$, which is contrasted to that of the loss $\gamma > 0$.

1.2 EP phase transition

Figure 1(**b**) shows how the system response changes when the coupling rate is fixed to κ and the γ of the balanced gain and loss is varied. The left and right plots respectively show the eigenmode frequencies (the real part of the complex eigenfrequency) with reference to the single cavity mode frequency ω_0 and their net loss rates (the imaginary part of the complex eigenfrequency) for which negative values mean

*1 Evanescent wave: A weak light wave that enters a medium with exponential spatial attenuation. It appears when the light with a certain wavelength is reflected from a medium that has no propagation mode for that wavelength, such as a photonic crystal or mirror.

gain. When $\gamma = 0$, which corresponds to the Hermitian system, the two eigenmode frequencies are split by 2κ by the coupling. The eigenmode distributions are two orthogonal states termed symmetric and antisymmetric. As γ increases, the frequency splitting decreases then changes abruptly toward zero near $\gamma = \kappa$. In this case, because both eigenmodes distribute an equal field intensity for the two cavities with balanced gain and loss, their net loss or gain rates are exactly zero. When $\gamma > \kappa$, the two mode frequencies are the same. In contrast, the eigenmodes' loss or gain rates split sharply into positive and negative values. Despite the fact that the cavities are supposed to be coupled, the eigenmodes become localized by the increase in γ; one concentrates in the cavity with gain, hence amplified, and the other is in the lossy cavity, thus damped. When the gain, loss, and coupling rates are equal ($\gamma = \kappa$), the eigenmode frequencies coincide, and the net loss or gain rates remain zero just before the bifurcation. What happens is not the accidental degeneracy of two different states with the same complex frequency; the distributions of the two modes rather become completely the same. Thus, there is only a *single* state. The degeneracy in this sense is a phenomenon peculiar to non-Hermitian systems and termed an EP. It can also be said that an EP is a phase-transition point from modes spreading over the entire system to those localized in cavities with gain or loss.

To date, a number of unconventional phenomena based on this EP phase transition have been reported, and readers can refer to a previous review article [2]. Examples include non-reciprocal propagation[*2], single-mode oscillation, and the enhancement of frequency perturbation effect, each of which has a good potential for practical use. Non-reciprocal propagation is a necessary condition for an optical isolator that protects a laser against instability by undesired optical feedback. Although integrating an optical isolator into a photonic circuit is technically difficult, it is an important element to complete optical information processing within a chip. Unfortunately, the non-reciprocal property near an EP is valid only for a certain range of the input light intensity because it is based on gain saturation. Thus, further studies are needed to pave the way for achieving a practical isolator based on an EP.

2. Observation of EP degeneracy by coupled photonic crystal laser

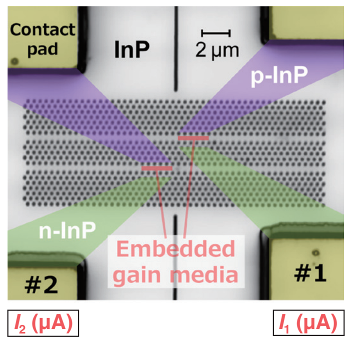
There are very few examples of observing EP degeneracy in photonics because of certain technical problems. One issue is the need for precise control of gain and loss. An EP is actually a point in the gain and loss parameter space, around which the complex eigenfrequencies vary greatly. Therefore, to observe EP degeneracy, it is necessary to control the gain and loss of each cavity independently and continuously. Another issue is the change in individual cavity frequency in controlling gain and loss. Regarding coupled cavities with the above-mentioned controllability, integrated systems of multiple semiconductor lasers are considered first. However, since driving them is accompanied by the generation of heat and free carriers, the real part of the refractive index of each cavity medium also changes when the gain and/or loss difference is introduced. As a result, the resonant frequencies of the two cavity modes diverge. Because this frequency detuning is known to lift EP degeneracy, it is necessary to use lasers with high excitation efficiency as much as possible to minimalize the impact of such an effect.

2.1 Current-injected photonic crystal laser

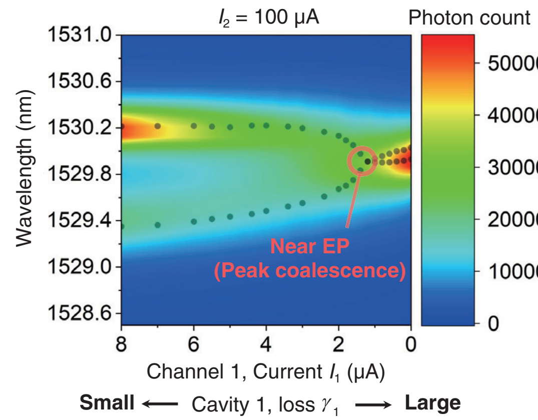
We fabricated the coupled system of two current-injected photonic crystal lasers [3] shown in **Fig. 2(a)**. The system is structured on an indium phosphide (InP) thin film suspended in air. It has a two-dimensional photonic crystal with an array of air holes with a diameter of about 200 nm. Two wavelength-scale gain media[*3] with quantum wells (red rectangles in the figure) are embedded in line defects without air holes and work as nanocavities. In addition, p-doped layers (purple parts) and n-doped layers (green parts) are formed in the oblique directions from the four electrodes (yellow parts), constituting two in-plane current-injection channels. Because this structure suppresses the leakage current between the electric channels, the gain and loss of each nanocavity can be controlled independently by current injection. To date, by using such a photonic crystal laser on the basis of a buried heterostructure nanocavity, we demonstrated the smallest laser threshold current in the

*2 Non-reciprocal propagation: Propagation under the condition that the scattering matrix representing the input and output relation for an optical component is asymmetric because of the magneto-optical, nonlinear optical, or time-modulation effects.

*3 Gain medium: A medium that can amplify light in the spontaneous emission wavelength range by stimulated emission based on the population inversion of electric carriers. Its activation requires short-wavelength light irradiation (optical pumping) or current injection (electric pumping). Our experiment exploited the property that a gain medium with no or small injection current acts as an optical absorber.



(a) False-color microscope image of the current-injected photonic crystal lasers



(b) I_1 dependence of the emission spectrum for I_2 = 100 μA. Black points: theoretical eigen-wavelengths.

Fig. 2. EP phase transition of current-injected photonic crystal lasers.

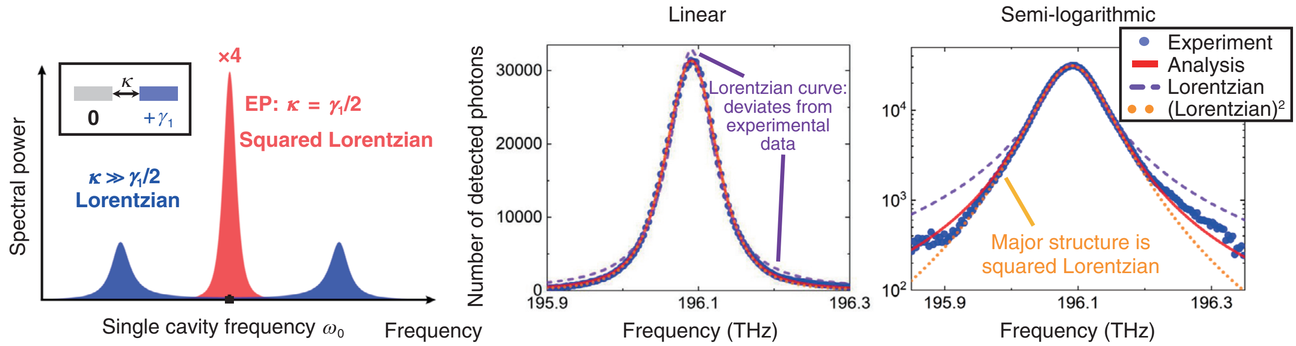
world [4]. The low current drive of our system minimalizes the detrimental effect of the cavity-frequency detuning due to heat and carriers.

In Fig. 2(a), the right and left cavities and current channels are numbered 1 and 2, and the inter-electrode current values for channel 1 and 2 are denoted as I_1 and I_2, respectively. The emission spectrum of the system was measured while I_1 and I_2 were varied. As a result, when I_2 was fixed at 100 μA and I_1 was decreased, a clear EP phase transition was observed. **Figure 2(b)** shows the color plot of such emission spectra for different I_1. Here, I_2 = 100 μA is the condition to compensate for the loss γ_2 due to absorption and radiation in cavity 2 ($\gamma_2 \sim 0$). However, a finite loss γ_1 of resonator 1 remains. Consequently, the entire system does not oscillate, and weak spontaneous emission of photons is hence observed. As I_1 diminishes, the two spectral peaks indicating coupled modes approach each other and eventually coalesce. This is because the difference in the loss of the two cavities is enhanced by the increase in γ_1, resulting in the variation of the eigenmode frequencies similar to that in Fig. 1(b). By fitting the spectra using a theoretical model, we can estimate the resonance frequency of each cavity mode, cavity coupling κ, and loss γ_1. We found that the system was very near the exact EP when I_1 = 1.4 μA. The detrimental frequency detuning of the two cavities is also very small. This can be seen from the fact that the theoretical eigen-wavelengths (black points in Fig. 2(b)) calculated from the fitting result are aligned with a point in the relevant region. If I_1 is further decreased, the peak photon number increases in spite of the magnified loss. This is thought to be because one of the eigenmodes is localized in resonator 2, which has a large injection current, becoming less susceptible to the loss of resonator 1. This intensity recovery also supports the EP phase transition illustrated in Fig. 1(b).

2.2 Spontaneous emission spectrum at the EP

We also clarified that the spectrum near the observed EP mentioned above indicated the peculiar enhancement of spontaneous emission. Even though the loss of one cavity is compensated and the other has a loss, the system with a large coupling exhibits a spontaneous emission spectrum that is expressed as the sum of two split Lorentzian functions*4 (blue spectrum in **Fig. 3(a)**). In contrast, the emission spectrum of the EP state takes the shape of the *squared* Lorentzian function (red spectrum in Fig. 3(a)) [5]. When the system can be approximated as a Hermitian one, the two modes are almost independent. Thus, even if their peaks coincide accidentally, the emission spectrum will only be the sum of them, that is, a Lorentzian function with twice their peak intensity. In stark contrast, the two modes degenerate into exactly

*4 Lorentzian function: The name of a function that represents the shape of the power spectrum of a general resonator response that exhibits exponential energy decay (in the present case, radiation based on spontaneous emission). If the system suffers from significant noise, the spectrum is disrupted and its shape becomes a Gaussian function with a broader linewidth. The reliable spectrum analysis for our experiment was enabled by both low-noise current drive of the device and low-noise spectroscopic measurement by long-time integration.



(a) Change in the emission spectrum at the EP. The EP condition for $\gamma_2 = 0$ is $\kappa = \gamma_1/2$.

(b) Spontaneous emission spectrum very near the EP (I_1 = 1.4 μA, I_2 = 100 μA). Left: Linear scale; Right: Semi-logarithmic scale.

Fig. 3. Enhancement of the system's spontaneous emission due to EP degeneracy.

the same state at the EP, exhibiting constructive interference in the spectral domain. Suppose we vary only the coupling κ that always preserves the energy so that the system is dragged to the EP condition while keeping the other parameters constant. In this case, we can measure the impact of the spectral change induced purely by EP degeneracy. Because of the maximum intensity change due to the interference, the peak intensity of the EP spectrum (colored red) is four times (= $(1 + 1)^2$) larger than those of the split Lorentzian peaks (blue). From the energy conservation, the total integrated powers for the two spectra in Fig. 3(a) are equal, and the loss of the eigenmodes for them is also the same. Despite this, the peak intensity of the EP is enhanced via the spectral change in which the shape becomes squared-Lorentzian; thus, the linewidth becomes narrower than the Lorentzian peaks for the large coupling.

Our system can control the gain and loss of each laser but not the coupling between the lasers. In our experiment, unfortunately, the effect of reducing the peak intensity by increasing γ_1 was superimposed on the measurement results. Thus, the directly observed ratio of the peak-intensity enhancement by the EP is about 30%. However, as shown in **Fig. 3(b)**, we also observed that the emission spectrum at I_1 = 1.4 μA, which was closest to the EP, was a squared Lorentzian function. This result indicates that the system is under an almost exact EP degeneracy. This means that the effect of EP degeneracy can be clearly observed if the system approaches the states at which its complex-eigenfrequency splitting is small enough compared with the linewidths of the modes.

3. Future outlook

In this article, we introduced the observation of EP degeneracy with our current-injected photonic crystal lasers. We are now conducting experimental demonstrations of our other theoretical proposals, such as the control of group velocity using an EP [6] and that of photonic topology by gain and loss [7], by using more large-scale photonic crystal laser arrays. We are also exploring new principles and phenomena in non-Hermitian nanophotonics.

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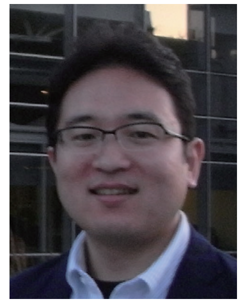

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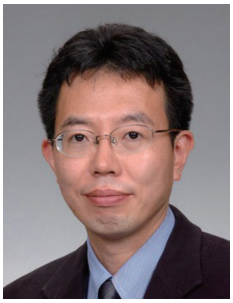

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Optical Device Technology for Next-generation Computing Using Light

Akira Okada and Toshikazu Hashimoto

Abstract

The performance of conventional computers, which have supported the infrastructure of our digital society and developed in accordance with Moore's law, seems to be approaching its limits. To solve many social issues and achieve a safe, secure, and prosperous society, next-generation computers with performance far beyond that of conventional computers, such as quantum computers, are expected. This article outlines the possibilities of next-generation computers that *compute using light* and optical device technologies introduced in the Feature Articles of this issue.

Keywords: next-generation computing, optical computing, optical devices

1. Introduction

Digital technologies used in all aspects of society, including smartphones, consumer electronics, automobiles, the Internet, public infrastructure information systems, finance, and commercial transactions, have become a social infrastructure. In addition, communication technologies that facilitate the coordination of distributed digital information and new digital technologies such as artificial intelligence (AI) and blockchain are having a significant impact on society. Sustainable development of digital technology, which is the foundation of society, is essential for solving many social problems, including energy problems, and for achieving a safe, secure, and prosperous society. Digital technology has continued to develop by increasing the integration of semiconductor integrated circuits that execute calculations, achieving both high performance and low power consumption. Moore's law, which states that the number of transistors in a semiconductor integrated circuit doubles every two years, is widely known as a symbol of this trend. However, the miniaturization of semiconductor integrated circuits is said to be approaching its physical limits, pointing to the limits of Moore's law, which has been maintained for half a century. In addition, the explosive growth of AI, which executes machine learning using more than one trillion parameters, is driving the need for increased computing power beyond Moore's law [1]. For example, a high-performance AI language model called GPT-3, published by OpenAI, consumes 1287 MWh of power when trained on the largest model. This is equivalent to the power consumption of an average Japanese household for approximately 300 years [2].

To overcome these challenges, there is a strong demand for the emergence of next-generation computers that can achieve performance far beyond that of conventional computers with low power consumption, not only by developing semiconductor integrated circuit technology but also using other methods.

The Feature Articles in this issue focus on computing technology using light, which has been attracting attention as a next-generation computing technology, and introduce the optical device technologies used for it. In light-based computing, it is necessary to consider how to represent information in the state of light and how to execute computing using the information represented using light. In the following sections, we review the advantages of representing information as a state of light and computing in such a state as information processing for next-generation computing as well as the optical device technologies required for light-based computing.

2. Information processing using light for next-generation computing

A term similar to information processing is signal processing. Using the analogy of manufacturing at a factory, information corresponds to parts, signals correspond to packages containing parts, signal processing corresponds to transportation such as sorting and transshipment, and information processing corresponds to the manufacturing process by using the contents of the package to make something new.

Just as the upper limit of the production capacity of a factory can be roughly estimated by the upper limit of the flow of goods, we first consider how much light can handle signals and the information they contain, including from the viewpoint of signal processing. Let us consider how information processing can be developed by incorporating light, which has been used in signal processing, in the same manner that manufacturing technology has greatly developed through the line-production system that integrates the manufacturing process and transport of goods.

Optical fiber communication is a typical example of superimposing information on light. In such communication, signal processing is executed to convert information into light intensity, frequency, and phase to transmit information. To provide an optical communication line, optical signals are distributed using an optical splitter, wavelength-multiplexed signals are separated or bundled using an optical multiplexer/demultiplexer filter, or processed in accordance with the frequency of the optical signal using an optical frequency filter. These can be regarded as a type of signal processing using an optical functional device. The signal superimposed on the light is a digital signal, and the information extracted from the light is processed using a digital filter to remove the noise contained in the phase, frequency, and amplitude. Therefore, signal processing and information processing are limited by the processing speed of electronic circuits.

In optical fiber communication, ultrahigh-speed transmission experiments at 100 Gbit/s-class modulation rate frequencies have already been demonstrated. In contrast, more information can be superimposed on light. For example, light with a wavelength of 1.5 μm is an electromagnetic wave with a frequency of about 200 THz, and light with an intensity of 1 mW can be thought of as a stream of about 7.55×10^{15} photons per second, leaving a great many degrees of freedom. However, to process information beyond the processing speed of electronic circuits, it is essential to compute with light because it is necessary to manipulate lightwaves and photons beyond the processing speed of electronic circuits. **Figure 1** shows the relationship between signal processing and information processing with respect to the granularity of information processed using light. When manipulating a digital-signal sequence or a single symbol of a digital signal, light is mainly used as a carrier wave processed using an optical filter as an element for signal processing that is superimposed on light. In information processing using light, however, light is treated as an analog signal wave, or the quantum state of light is used to superimpose information on it and manipulate the state of light to process information. In optical signal processing, optical circuits are used in cooperation with electronic circuits, whereas in optical information processing, optical operations are executed in a closed manner within an optical circuit. Optical operations for information processing are executed by precisely controlling optical interference, homodyne detection, and autocorrelation to obtain amplitude and phase information, then combining them. As described in the Feature Articles in this issue, the basic operations of optical neural networks [3] and optical quantum information processing [4, 5] are beginning to be demonstrated in actual optical circuits. Optical information processing is considered a promising candidate for next-generation computing technology.

3. Optical device technologies for computing using light

By superimposing information on the enormous degrees of freedom of the state of light, we can see the potential of optical computing technology beyond that of conventional computers. In this section, we consider what type of computing is possible with information represented using light and what kind of devices will be needed to achieve this.

Digital technology has mainly used Neumann-type computing, which executes sequential logical operations on data based on programs. High-speed logic operations, including information transmission between processors and peripheral devices, are important for the development of digital technology. Non-Neumann-type computing, on the other hand, uses a method different from conventional sequential logic operations. When using light, as mentioned above, non-Neumann-type operations can be executed instead of sequential logic operations using the enormous amount of light states, enabling large-scale,

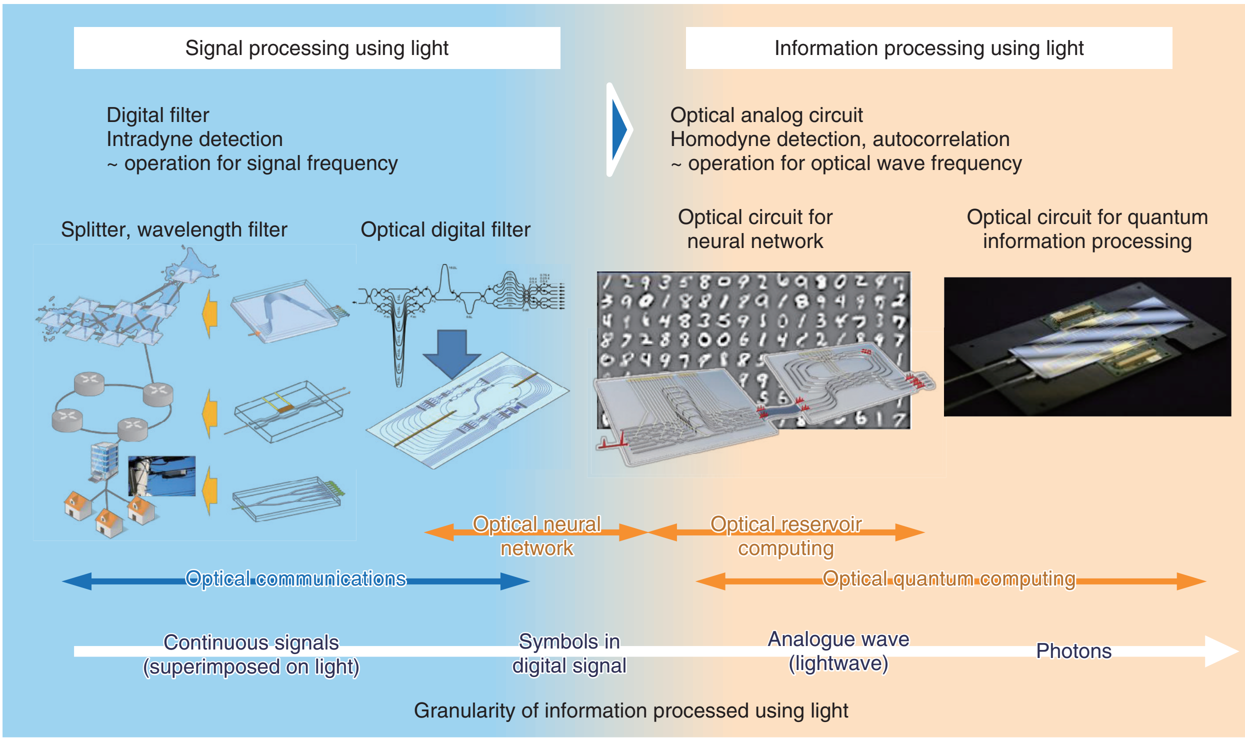

Fig. 1. Relationship between signal processing and information processing with respect to the granularity of information processed using light.

high-speed computing that is not limited by the processing speed of electronic circuits. **Figure 2** shows the correspondence between Neumann-type and non-Neumann-type computing and optical device technologies. For optical devices, lightwaves and photons must be handled well to achieve computing using light, while high-speed and broadband performance is needed to accelerate logic operations in computing. In the direction of high-speed and broadband, opto-electronic convergence technology [6] is expected to contribute to improving the performance of current computing systems, including optical interconnection, in response to high-capacity transmission technology used for optical fiber transmission. When considering wide-area networks, conventional optical devices such as linear optical circuits also support this area of technology.

From the viewpoint of handling lightwaves and photons, nonlinear optical elements for generating correlation of lightwaves superimposed with information, optical circuit technology for generating complicated correlation and operating calculation using light as a system, and systematization technology including electronic control are important. When using photons, a quantum light source, corresponding to a laser light source in optical communications, is required to generate quantum states of light. These devices enable non-Neumann-type computers such as coherent Ising machines [7] and optical reservoir computers/optical neural networks [3]. Quantum light sources and optical circuits for optical quantum information processing are also considered essential devices for implementing optical quantum computers, and their basic operation for optical quantum information processing has been demonstrated [4, 5, 8].

Neumann-type and non-Neumann-type computation technologies are not mutually contradictory, but are combined or complemented in accordance with the computation target and computation purpose, and the equipment-integration technology that integrates them as hardware is important for constructing practical systems [9].

In the following three Feature Articles in this issue, we introduce optical device technologies for optical quantum computers, optical neural networks, and optical reservoir computers, which can be called *computing using light* in the next generation of

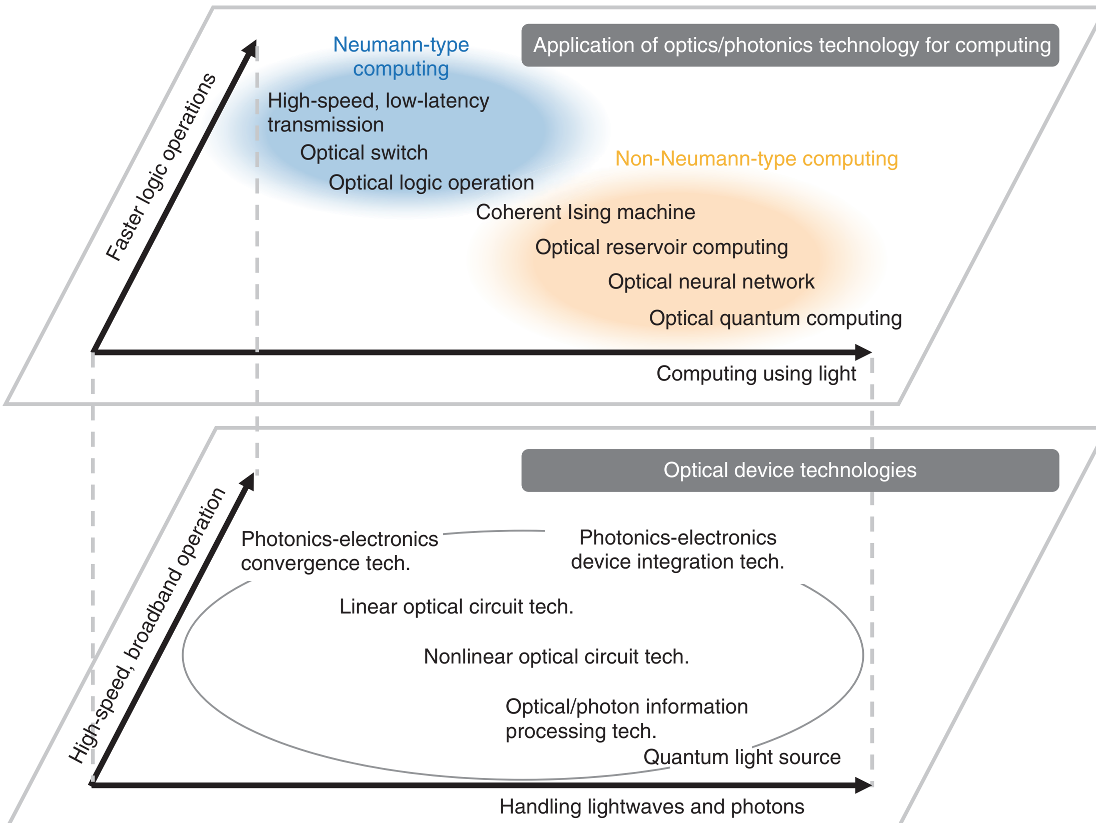

Fig. 2. Correspondence between computing and optical device technologies.

computing. The first article, "Broadband Continuous-wave Optical Quadrature Squeezer for Ultra-fast Optical Quantum Computers" [10], introduces the periodically poled lithium niobate (PPLN) waveguide technology, an optical nonlinear device, and its application to quantum light source technology. In the next article entitled "Optical Circuit Technologies for Next-generation Computing Using Light" [11], linear optical circuits and their applications for optical quantum computing are introduced. In the third article "Photonic Implementation of Reservoir Computing" [12], we introduce optical reservoir computing technology as an optical neural network technology that combines optical device technologies into a system and achieves large-scale sum-of-products operations.

These technologies enable cutting-edge research that incorporates a variety of technologies and are expected to become core technologies for advancing next-generation computing.

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Broadband Continuous-wave Optical Quadrature Squeezer for Ultra-fast Optical Quantum Computers

Takahiro Kashiwazaki, Asuka Inoue, and Takeshi Umeki

Abstract

An optical quadrature squeezer is expected to be a key device for high-speed optical quantum computing. We developed a high-gain and broadband optical quadrature squeezer by using a periodically poled lithium niobate (PPLN) waveguide. The squeezer is assembled as a pump-combiner-integrated module with four optical-fiber input/output ports. By improving the fabrication processes of the PPLN waveguide, we achieved a low-loss module that exhibits about 1-dB optical loss. By using this module, we successfully obtained continuous-wave 6-dB-squeezed light at over-6-THz sideband frequency even in a fiber-closed optical system with commercially available optical components. This fiber-compatible broadband quadrature squeezer will accelerate the development of optical quantum computers.

Keywords: periodically poled lithium niobate, optical quadrature squeezer, optical quantum computer

1. Introduction

Research and development of universal quantum computers has accelerated worldwide, and various computing methods have been proposed using superconducting circuits, trapped ions, photons, etc. [1, 2]. We are developing an optical quantum computer that uses the amplitude and phase of propagating light as an information carrier, similar to the current optical communication technology [3]. This is because an optical quantum computer has the potential of ultra-fast clock-rate computing thanks to the high frequency of light. We are aiming to develop an overwhelmingly large-scale and high-speed universal quantum computer using time-domain multiplexing and measurement-induced quantum manipulation [4]. The most important element of this optical quantum computer is a squeezed light source. In this article, we introduce the research and development of a squeezed light source, i.e., a squeezer, which is a key device for high-speed, large-scale, universal quantum computing.

2. Squeezed state of light and its application to quantum computers

Squeezed states are non-classical states in which the quantum noise in a non-commutative quantity (momentum and position, energy and time, etc.) is compressed. Due to the uncertainty relation, the noise for the other quantities is amplified. The quadrature-amplitude-phase squeezed vacuum state of light (or simply squeezed light) has compressed quantum noise of the sinusoidal or cosine component with a wave image, as shown in **Fig. 1(a)**. With a particle image, the squeezed light is an even-number photon state. By interfering two squeezed states with a half beamsplitter, we can deterministically generate a quantum entangled state (with 100% probability) [5]. Using multiple squeezed light sources and delay line interferometers, we are able to generate a time-domain multiplexed large-scale quantum entangled state (**Fig. 1(b)**) [4]. This state is called an optical cluster state and used as a resource for measurement-based quantum computation. By measuring one qubit of the optical cluster state, we can execute some quantum gates to other qubits with a methodology

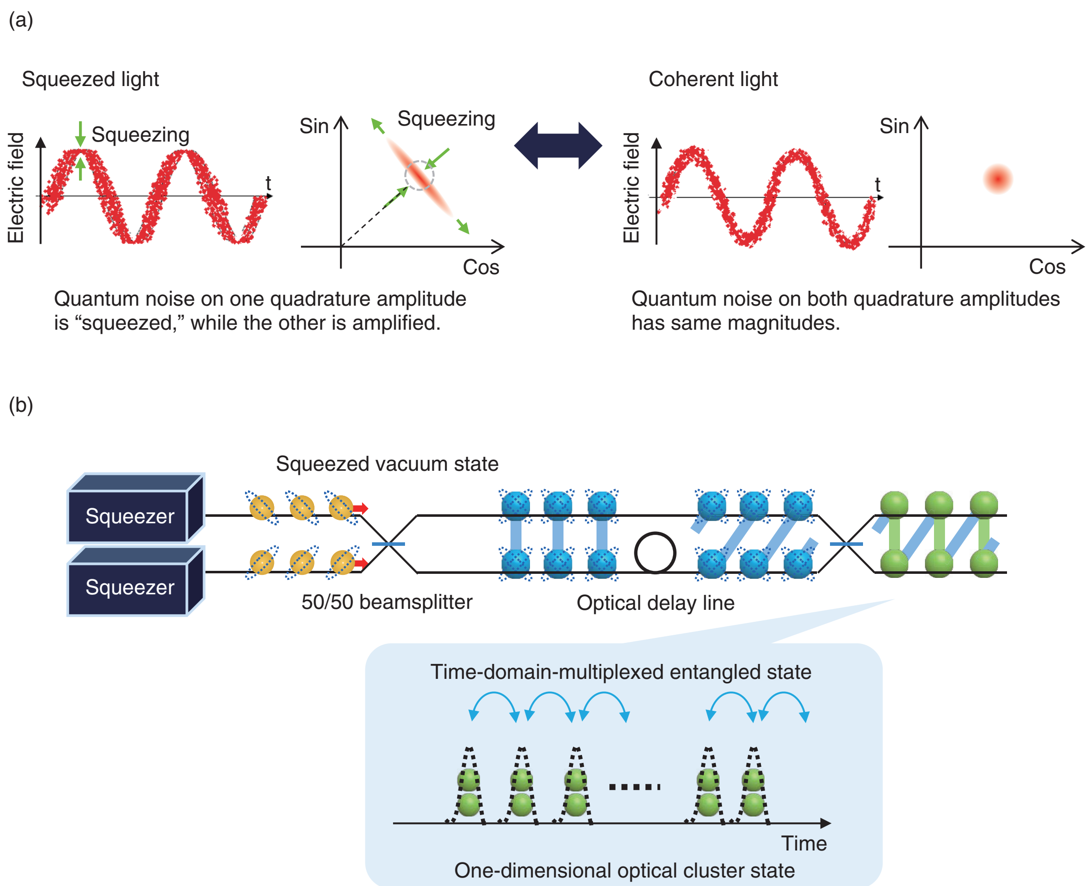

Fig. 1. (a) Image of quantum noise in squeezed light. While coherent light has quantum noise equal to the sinusoidal and cosine components, squeezed light has compressed one side of the noise. The quantum noise of the other side becomes larger due to the requirement of the uncertainty principle. (b) A method for generating multiplexed large-scale quantum entangled states in the time domain using squeezed light.

such as quantum teleportation [6].

To develop a high-speed, large-scale, universal quantum computer, continuous-wave broadband high-level squeezed light is required. This is because the continuous wave and broadband nature of squeezed light maximizes time resources and enables high-speed and large-scale computational performance that cannot be achieved with other methods [7]. High-level squeezed light has quantum superposition states with even-photon-number components, which is important for quantum error correction [8].

3. PPLN-based quadrature squeezer module

Squeezed light can be generated from a nonlinear optical phenomenon. In 1985, the first generation of squeezed light was demonstrated using the third-order nonlinear optical effect of natrium vapor [9]. Since then, squeezed light has been generated in a variety of ways [10], and second- and third-order nonlinear optical effects in solids have become mainstream. Waveguide-type optical parametric amplifiers based on second-order nonlinear optical crystals are expected to exhibit broadband characteristics in principle [7]. However, nonlinear optical devices are generally difficult to fabricate, and it has been difficult to generate high-level squeezed light. To generate a high level of squeezed light, the optical waveguide must have low loss, exhibit high nonlinear optical properties, thus be resistant to strong excitation light. Low loss is required because squeezed light is easily degraded by contamination of the vacuum field associated with optical loss. We have been developing direct-bonded periodically poled lithium niobate (PPLN) waveguides, as shown in **Fig. 2(a)** [11]. Lithium niobate is a ferroelectric material with

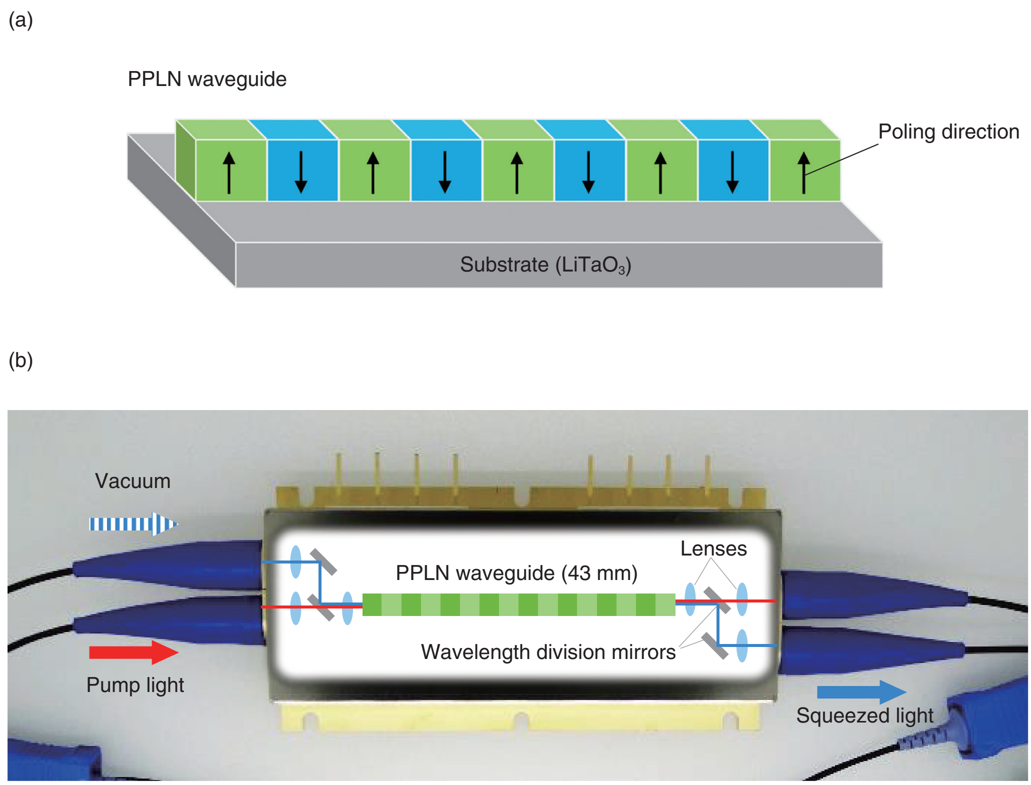

Fig. 2. (a) Schematic view of a PPLN waveguide. The waveguide core is directly bonded to the substrate. (b) Fiber-coupled optical parametric amplifier. Wavelength-division mirrors and lenses are installed inside so that the pump light and squeezed light are separated and injected to each output optical fiber [14].

a wide transmission bandwidth and high second-order nonlinear optical coefficient. Thanks to its periodical poling, it is possible to enhance the nonlinear interaction of light passing through the waveguide. By bonding the waveguide directly to the substrate without using any adhesive, we fabricated devices that can operate even under pump light with watt-level intensity. Our fabrication techniques have recently enabled low-loss, high-gain optical parametric amplifiers with high pump-light tolerance.

Our group is also developing modular optical parametric amplifiers that can be easily coupled with fiber optics [12–14]. This is to enable the construction of maintenance-free optical systems in anticipation of practical applications. Quantum optics experiments had been conducted on an optical table with many mirrors and lenses arranged with high precision to verify the proof-of-principles. These optical systems require constant precise adjustment, and this has been a problem that needs to be solved for practical applications. As shown in **Fig. 2(b)**, our module has a structure in which the pump light and squeezed light are separated inside the module, and each is efficiently coupled to an optical fiber [12–14]. This fiber-pigtailed module will greatly advance the development of practical-use optical quantum computers because we can combine various highly reliable and high-performance optical components, which are cultivated in the field of optical communications.

4. Squeezing-level measurement

The squeezing levels have conventionally been measured by balanced homodyne detection [15]. With this method, the squeezed light interferes with a local oscillator, the frequency of which is the same as the center frequency of the squeezed light, by using a half beamsplitter. The difference between the output intensities of the two paths is then extracted as an electrical signal by using a balanced photodetector. Accordingly, the bandwidth of the squeezed light measured using balanced homodyne detection is limited by the bandwidth of the electrical circuit up to a few gigahertz. Therefore, we developed a method for

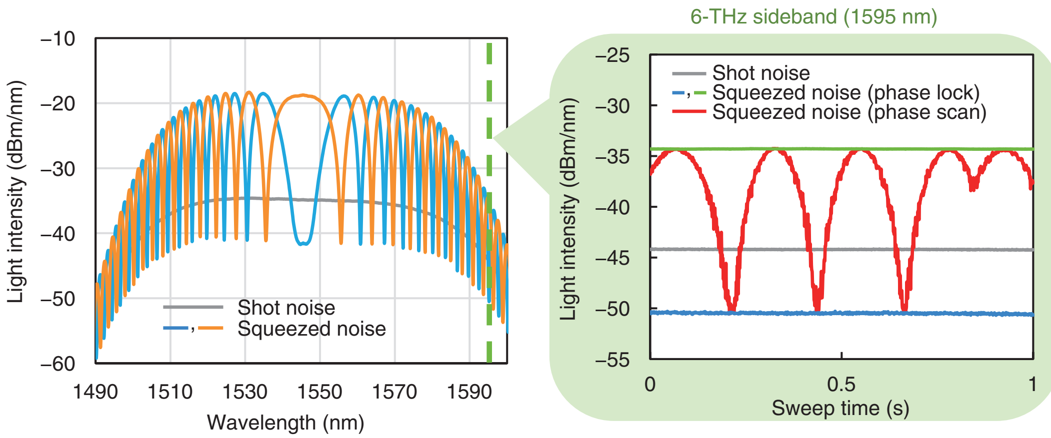

Fig. 3. Quantum-noise-intensity measurement results for squeezed light. The noise level was more than 6 dB lower than the shot noise level. The squeezing level was maintained over the broadband component above 6 THz [14].

measuring quantum-noise intensity up to THz-class broadband components by further optical parametric amplification of the squeezed light [16]. This means that the quantum information is converted directly into *classical* light, whereas previous methods (balanced homodyne detection) convert it onto the classical state of an electrical signal. **Figure 3** shows the results of noise-intensity-level measurements. The experimental results indicate that the noise of the squeezed light is suppressed by more than 6 dB compared with the shot-noise level, even for THz-order sideband components [14]. This value is more than the 4.5 dB required to generate two-dimensional optical-cluster states, which enables multi-qubit quantum computation. This is the world's highest value for squeezing using a waveguide-type optical parametric amplifier with an all-optical-fiber-closed system.

5. Conclusion

We reported on the generation of continuous-wave, broadband squeezed light for the development of a high-speed, large-scale, universal quantum computer. The squeezing of 6 THz and more than 6 dB was achieved using an optical parametric amplifier consisting of a PPLN waveguide, which was developed by NTT. The device can be implemented as a fiber-coupled module to enhance compatibility with optical communication components and is being fabricated in anticipation of the future development of quantum computers. We aim to achieve a higher level by improving the device-fabrication technique and optimizing the design and are attempting more than 10-dB squeezing for fault-tolerant quantum computation.

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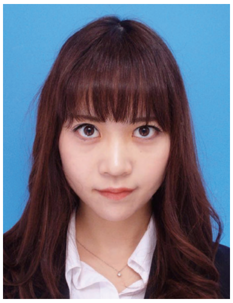

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Optical Circuit Technologies for Next-generation Computing Using Light

Toshikazu Hashimoto, Junji Sakamoto, and Shiori Konisho

Abstract

To sustainably achieve a society in which digital technologies have penetrated in various forms such as smartphones and cloud services, computing technologies that greatly exceed the current performances are becoming important. NTT is advancing research and development of computing technology using lightwaves/photons by applying device technology for communications using optical waveguides. In this article, we introduce optical circuit technology mainly for optical quantum computing as an example.

Keywords: optical circuits, planar lightwave circuits, optical quantum computers

1. Optical circuit technology for computing using lightwaves

A variety of optical devices have been developed for optical fiber communications by using planar lightwave circuit (PLC)* technology (**Fig. 1(a)**), in which the circuit is fabricated by combining optical fiber and semiconductor manufacturing technologies [1]. PLC technology is considered a promising device technology for computing using light as an optical circuit technology capable of integrating linear optical elements.

Electronic devices, such as transistors, three-pole vacuum tubes, and three-terminal regulators, can be classified as three-terminal devices. They have inputs and outputs, and the desired output can be obtained by reflecting the control signals from the control terminals to the input state. A computer is composed of a very large number of transistors, which are three-terminal devices. In a vacuum tube (**Fig. 2(a)**), for example, the operation of the three-terminal device is controlled by the voltage applied to the intermediate terminal called the grid. Regarding optical devices, there are optical switches and optical modulators that drive control terminals from electronic devices, but from the viewpoint of computing using light, the input to the control terminals must also be light.

One such device that can be considered a three-terminal device is an optical interferometer. An optical interferometer outputs the interference light from multiple optical inputs. It is considered a three-terminal device by regarding some of the optical inputs as ports of light for control. **Figure 1(b)** shows the basic operation of a directional coupler, a type of interferometer often used in PLC technology. When two optical waveguides (paths of light) are brought close together, light is transferred from one optical waveguide to the other. By separating the optical waveguide at half the length of the complete transition, we can split the input light into two lights with phase difference by $\pi/2$. The input from the other optical waveguide is also divided into two lights with the phase difference of $\pi/2$. When these are input and superposed at the same time, and one is considered an input port and the other a control port, and if the output from the two waveguides on the output side is considered one output state, it becomes a three-terminal optical circuit that controls light by the phase difference between the light at the input and control ports.

An example of a device using this interferometer is an optical circuit called an optical 90-degree hybrid

* Planar lightwave circuit (PLC): An optical circuit that provides pathways for light using a silica microstructure on a silicon wafer based on optical-fiber fabrication technology and semiconductor manufacturing technology.

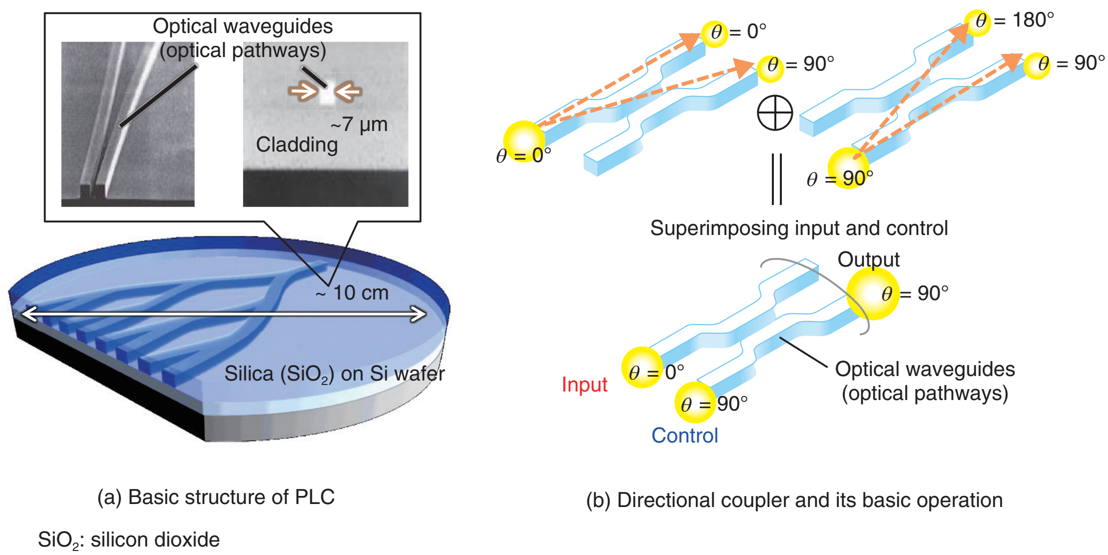


Fig. 1. PLC and basic operation of directional coupler.

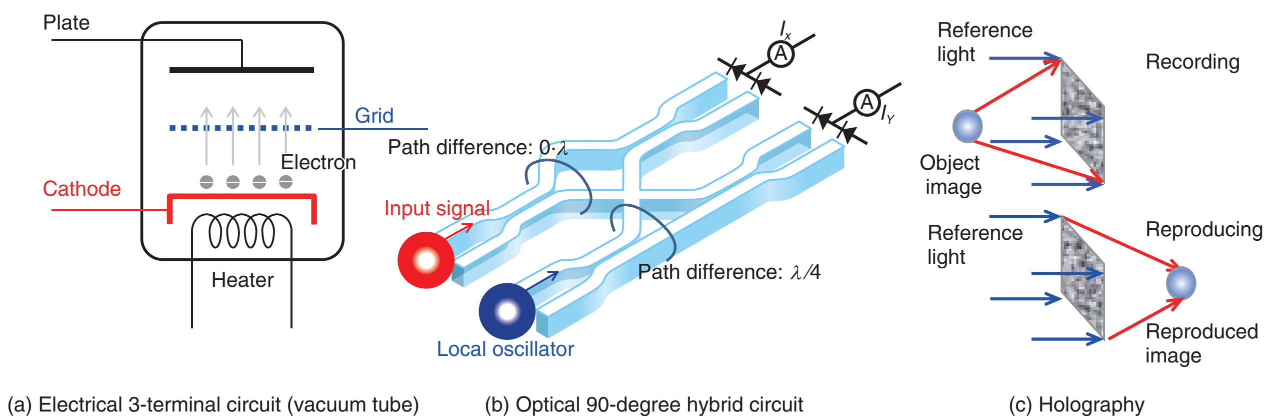


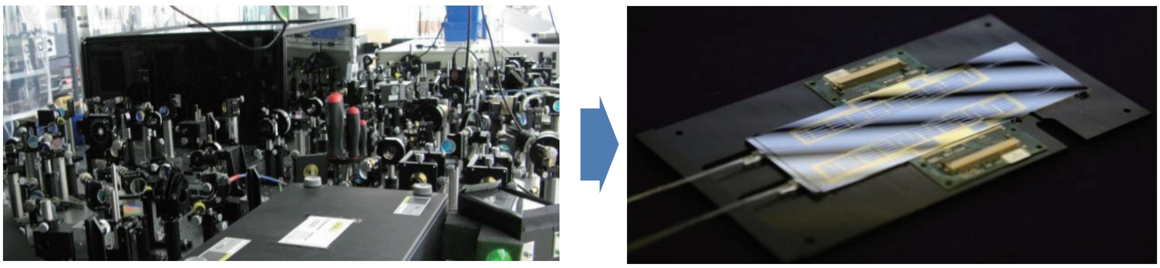
Fig. 2. Example of electrical/optical 3-terminal circuit.

circuit [1] (**Fig. 2(b)**), which can measure both the phase difference and amplitude of the input signal with respect to the local oscillator light (local coherent light) used in coherent transmission. In coherent transmission, local oscillator light with a constant frequency is used. In optical quantum information processing, which is introduced later, local oscillator light is combined with the entangled state as a control signal to enable quantum teleportation to obtain a desired output. For another example, the holographic recording process can be regarded as a three-terminal device for obtaining a Fourier transform image if the image light is used as an input and the reference light is regarded as a control light (**Fig. 2(c)**).

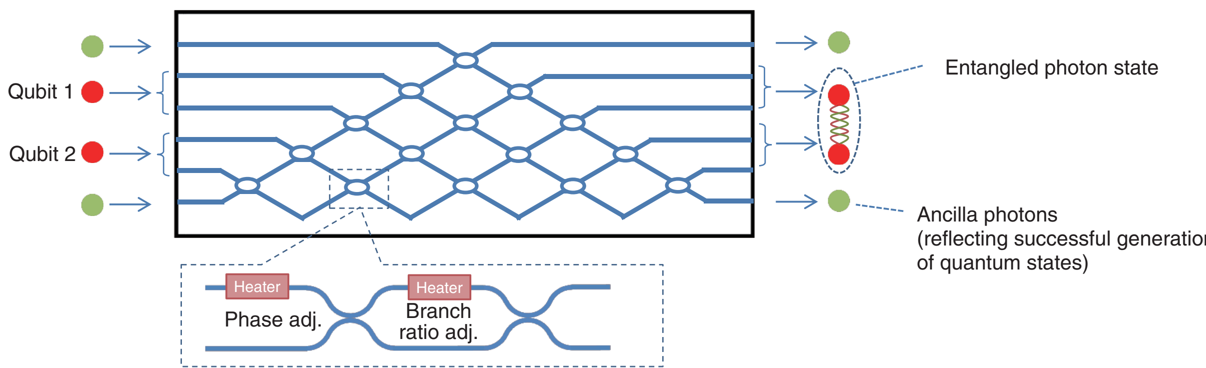
If an optical circuit in which multiple inputs interfere with each other can be regarded as a three-terminal device, it is expected to enable new information processing using light, similar to processing by a computer composed of vacuum tubes and transistors. Quantum information processing using optical circuits is introduced as a concrete example.

2. Quantum information processing using optical circuits

Quantum computers use superposition and



(a) Optical circuit by spatial optics with mirrors and lenses (left), and PLC for universal (right)



(b) Configuration of generating entangled photon state with optical circuit by PLC

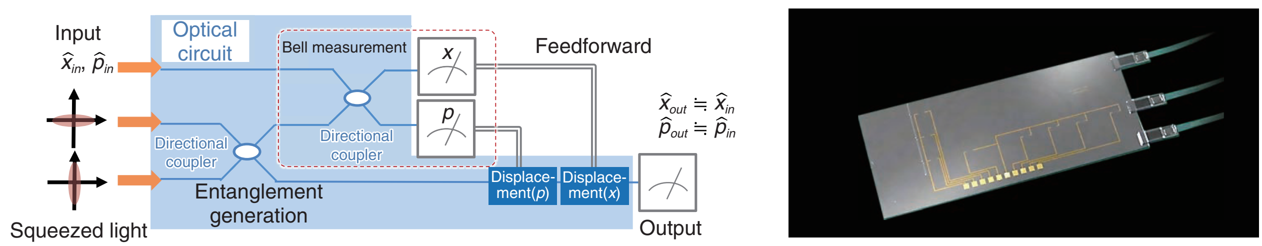
Fig. 3. Mode-type quantum-information-processing optical circuit.

entanglement of quantum states to solve problems that cannot be solved using a conventional computer in practical terms. Various physical quantum states and their implementations have been proposed for use in quantum computers, including superconducting circuits and ion traps. Optical quantum computers using photons are promising candidates of feasible quantum computers because they can operate at room temperature and at high speed. Optical quantum information processing using optical circuits is mainly divided into two types, mode (or path qubit) and continuous-variable, which are introduced below.

2.1 Mode-type optical quantum information processing

Mode-type optical quantum information processing uses photon states (mode) in optical waveguides. There are two methods of expressing a qubit. One provides a qubit as superposition of a state with and without a photon in one optical waveguide (single-rail representation), and the other expresses a qubit by superposition of a state with a photon in either waveguide using two optical waveguides (dual-rail representation). To achieve the nonlinear operation required for quantum information processing in a linear circuit, it is necessary to achieve it stochastically in combination with measurement. In the single-rail representation, it is difficult to distinguish whether a photon has disappeared due to loss or a change in the quantum state. However, the dual-rail representation always manipulates the state in which a photon is present, so it is easy to detect whether a quantum operation has succeeded by combining it with an auxiliary photon (ancilla photon). Using dual-rail representation and posterior selective processing of successful quantum states, research is being conducted to achieve larger-scale quantum computing.

NTT has fabricated the world's first 6 × 6 universal quantum optical circuit using PLC technology (**Fig. 3(a)**). Conventionally, it had difficult to ensure stability because of the extremely large size of the optical system constructed with spatial optics on an optical bench. However, by making it a chip, a compact and stable optical system was achieved. The configuration of the optical circuit is shown in



(a) Configuration of optical circuit for quantum teleportation

(b) Quantum teleportation circuit by PLC technology

Fig. 4. Optical circuit for continuous-variable-type optical quantum information processing.

Fig. 3(b). The part where the optical waveguides appear to intersect is equipped with a heater that locally changes the refractive index by the thermo-optic effect, and the phase and branching ratio can be adjusted. Although it may look like a complex circuit, it combines the basic operations of interfering photons in a directional coupler, allowing variable, arbitrary linear operation (6 × 6 unitary operation). In collaboration with the University of Bristol, we have confirmed that various types of quantum information processing can be executed with high precision [2]. Figure 3(b) shows the configuration of an optical circuit that generates an entangled state from two qubits in a dual-rail representation. To implement a practically useful quantum computer, it is necessary to further increase the scale, but in addition to increasing the number of waveguides, it is also necessary to develop a more advanced circuit configuration, such as post-selecting only successful quantum states reflecting the states of ancilla photons and transmitting them to the subsequent stages.

2.2 Continuous-variable-type optical quantum information processing

A quantum computer using a continuous variable system has also been proposed. With a continuous variable system, the quantum state is determined by measuring the interference state with the reference light by putting information on the phase and amplitude of the lightwave as in the case of radio or optical fiber communications. This is called projection measurement because the base of the state to be measured can be specified by changing the way the reference-light state interferes with the observed state. For example, a 90-degree hybrid circuit, as a measurement of the classical state, is, from a quantum mechanical point of view, a projective measurement (bell measurement) that detects photons in the mode corresponding to the entangled state (bell basis) of the input and reference light. By using the result of the bell measurement of one of the entangled states, quantum teleportation can be achieved by phase-shifting another one of the entangled states (**Fig. 4(a)**). This circuit is extremely important as a basic operation of measurement-type quantum computation, which executes quantum information processing by measurement with feedforwarding via a classical path. In cooperation with the University of Tokyo, we fabricated a PLC circuit that operates in the 850-nm band, as shown in **Fig. 4(b)**. As a preliminary study, we evaluated the squeezed light output from the circuit and confirmed a squeezing level of approximately 3.2 dB, which enables non-classical operation [3, 4]. To achieve a level sufficient for quantum computation, including quantum teleportation, we are now shifting to research on quantum information processing in the 1.5-µm band, where device technology for telecommunications can be widely applied, and are vigorously improving the characteristics, such as transmittance of optical circuits.

3. Future technology of optical circuit technology for computation using light

As we have seen, multiple inputs interfere with each other in a way that corresponds to a three-terminal element in an electronic circuit, enabling new information processing with light. In addition to the research introduced in this article, research on neural networks using optical circuits has been vigorously studied. However, how to scale a computational circuit using light is a major issue for its practical use as a computing technology in the future. When optical chips are connected and scaled, as with electronic devices, optical interference is lost or delayed when data transmission is converted to digital data. Even

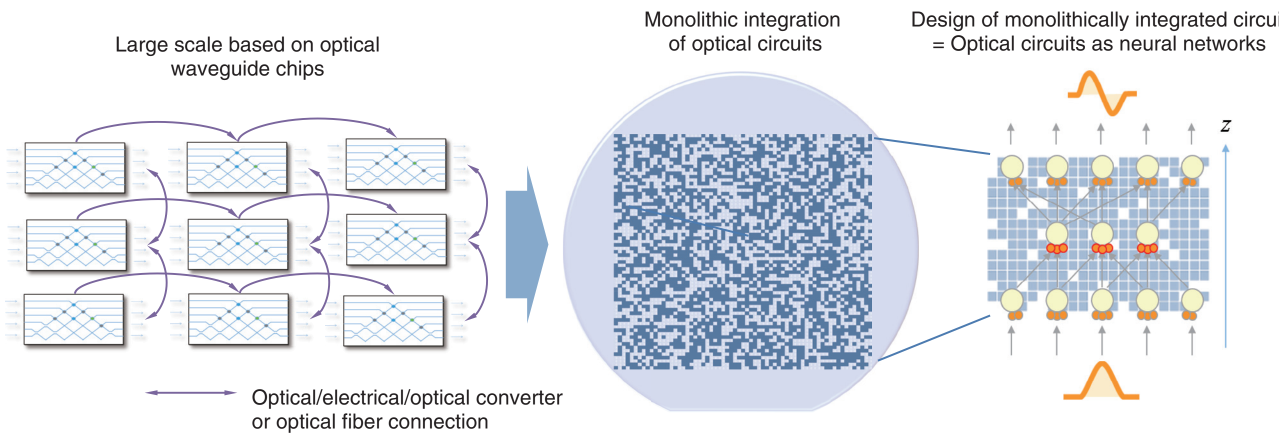


Fig. 5. Scalability and monolithic integration of optical circuits for computing using light.

when optical chips are connected with optical fibers, loss and phase shift become unavoidable (**Fig. 5**, left). Therefore, we need a different approach than combining elements such as electronic circuits and scaling them up. One method is to use the time domain to compute by using the entanglement/correlation between light pulses. Examples using the time domain include continuous quantum optical information processing using multiple pulses described in this article and optical reservoir computing introduced in the article "Photonic Implementation of Reservoir Computing" [5] in this issue. Another means of scaling up is to increase the spatial density. As long as optical interference is used, the size of the components of the optical circuit is limited to the size of the wavelength of light. However, in mode-type optical quantum information processing, for example, a method using multi-value states (qudits) with multiple waveguide modes instead of binary (qubit) states has been proposed. As an extreme case of infinitely increasing the number of modes on the basis of this idea, we can use an approach called *monolithic integration* of optical circuits, in which information is carried on the wavefront instead of the mode, and computing is executed by interference. The wavefront-matching method has been proposed as an optical-circuit design method that uses the entire refractive index distribution of an optical circuit, and it has been shown that the optical circuit corresponds to a neural network when the entire refractive-index distribution is considered an optical circuit [6] (Fig. 5, right). A neural network based on the evolution equation of the Schrödinger network [7] has also been proposed.

It is expected that optical circuit technology, which enables computing using light, will continue to be developed toward the next generation of computing technology in conjunction with the development of new technologies such as optical quantum computers and neural networks.

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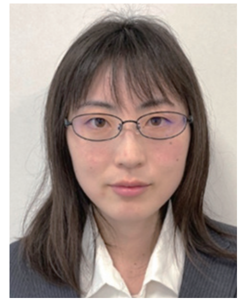

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Photonic Implementation of Reservoir Computing

Mitsumasa Nakajima, Takuma Tsurugaya, Kenji Tanaka, and Toshikazu Hashimoto

Abstract

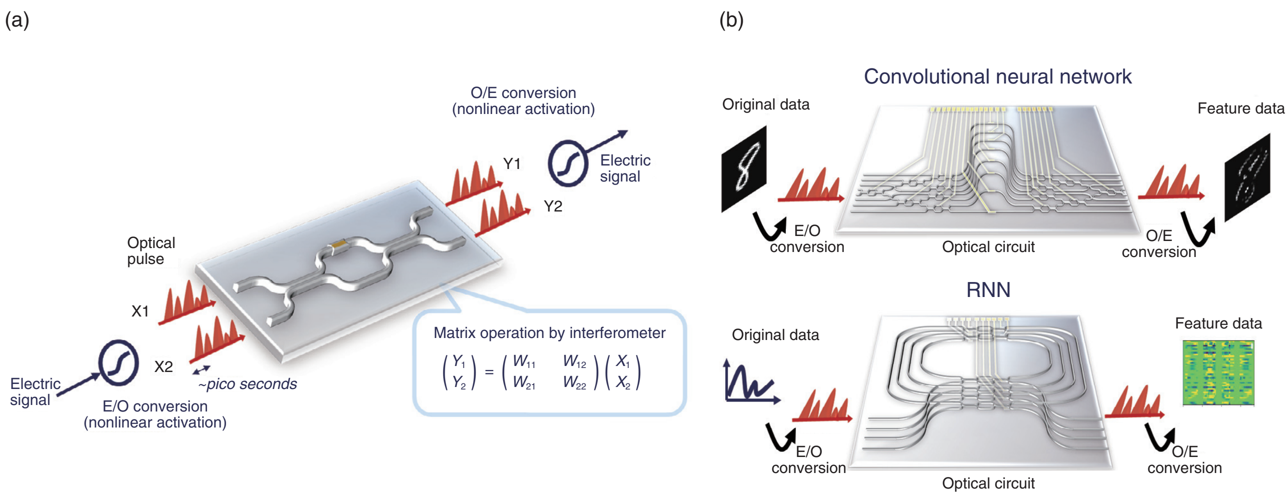
Today's computing for machine learning is carried out with digital electric processors, which have issues regarding energy consumption and processing speed, by emulating brain-inspired information processing. To address these issues, photonic devices, comprising a photonic neural network, are gaining much attention for achieving high-speed and energy efficient brain-inspired computations. We report on the photonic implementation of a simplified recurrent neural network called reservoir computing.

Keywords: photonic computing, machine learning, reservoir computing

1. Introduction

Recent large-scale information-transportation technology has been driven by the development of photonic devices, such as photonic transceivers, receivers, and switches. Due to these technological developments, the barrier between photonics and electronics has been lowered, which enables the integration of photonic and electric circuits into a single module. Such optoelectronic integration technology is now advancing for much larger-scale and energy-efficient optical transmission [1]. Optoelectronic integration has been gaining attention for applying photonic circuits as computation units, such as logic gate [2], matrix operation [3] and/or optimization solver [4], beyond the simple optical link function. These studies revived the development of optical computing, which was intensively studied during the 1980s. This revival is also related to the explosive evolution in artificial intelligence (AI).

Information processing in AI involves brain-inspired computational algorithms called artificial neural networks (ANNs). Their computation is based on a huge amount of matrix operations and nonlinear processing, which requires energy-hungry large-scale computational resources. As the demand for such computation is explosively increasing, the development of special-purpose AI hardware providing much faster and more energy-efficient computational resources has been intensively studied. The photonic implementations of ANNs are attracting interest because they have potential to reduce operational power, increase speed, and reduce latency beyond what is possible in electronic computing. Unlike digital calculation on conventional electronic circuits, photonic computing uses analog values, such as the intensity and phase of optical signals, as information. Its propagation and interference are considered as the computation. For example, when we input an optical signal to an optical interferometer, as shown in **Fig. 1(a)**, the optical signals interfere with each other. The output intensities can be considered the results of the matrix product of the input signals and parameters in the interferometer. This calculation is conducted only by high-speed light propagation and interference without principle energy consumption. More large-scale computation is possible by using the optical signal multiplexing technologies developed for telecom application, such as time, wavelength, and space division multiplexing. We can construct various ANNs by designing the configuration of an optical interference system, as shown in **Fig. 1(b)**.



E/O: electrical to optical
O/E: optical to electrical
RNN: recurrent neural network

Fig. 1. (a) Schematic of matrix product operation using photonic interferometer. (b) Examples of ANN emulations using photonic circuits.

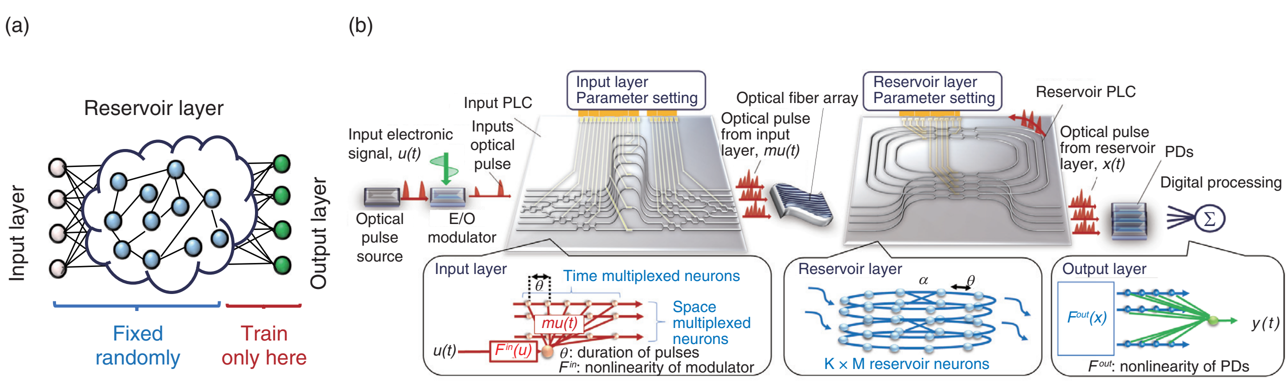


Fig. 2. (a) Overview of RC framework. (b) Schematic of our on-chip photonic RC architecture.

2. Reservoir computing and its photonic implementation

Reservoir computing (RC) is a type of recurrent neural network having recursive connections, as shown in **Fig. 2(a)**. In the RC framework, the weights of the input and reservoir layers are randomly fixed and not trained. Only the output weights are trained by linear regression such as the least squares method, which is much simpler than the training method used in standard ANNs such as backpropagation. In spite of the simple configuration, RC has shown excellent performance comparable to that of standard ANNs on a series of benchmark tasks such as speech recognition, economic forecasting, and action detection in video data. RC also has advantages from the viewpoint of photonic implementation. Standard deep ANNs require fine tuning of each weight through the use of the error back propagation algorithm, which requires highly accurate and uniform large-scale integration of tunable optical elements, which is a challenging issue for fabrication. The training time of a photonic ANN is generally much longer than that with electrical devices because the reconfiguration of optical weights takes milliseconds. In the RC framework, however, there is no need for any fine tuning of

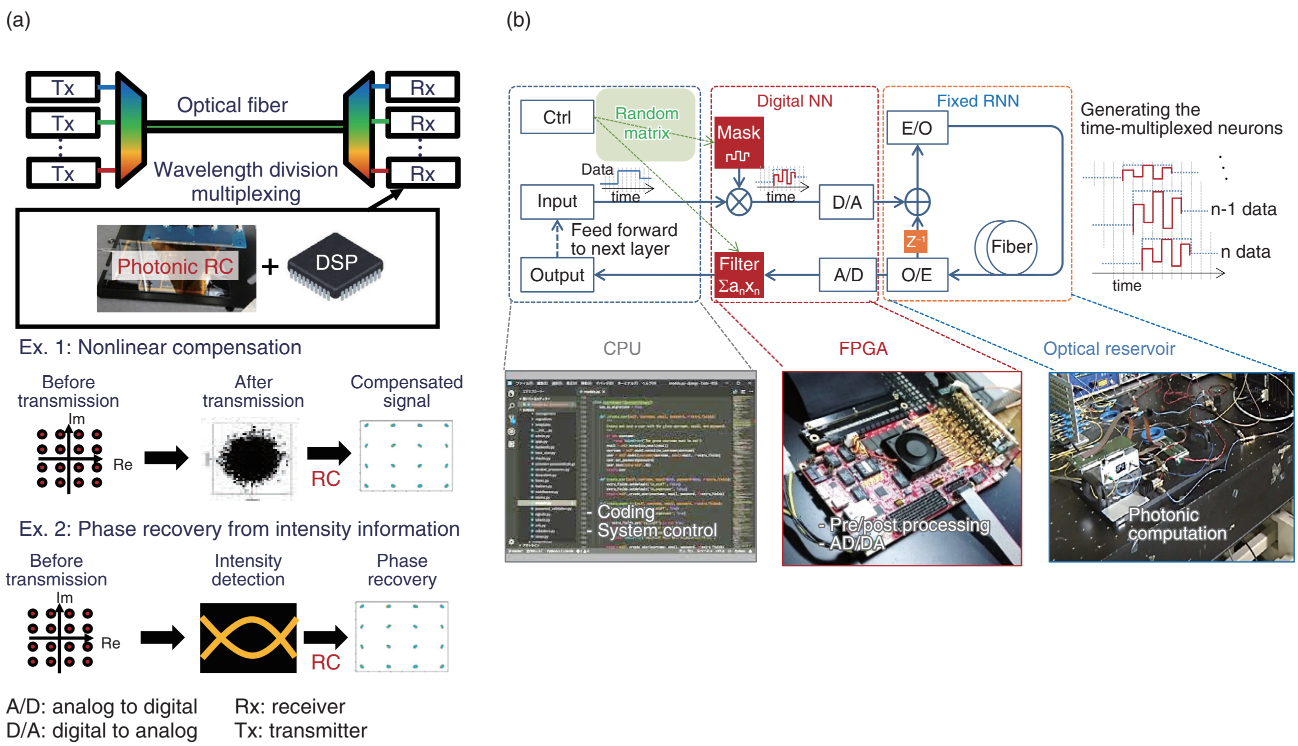


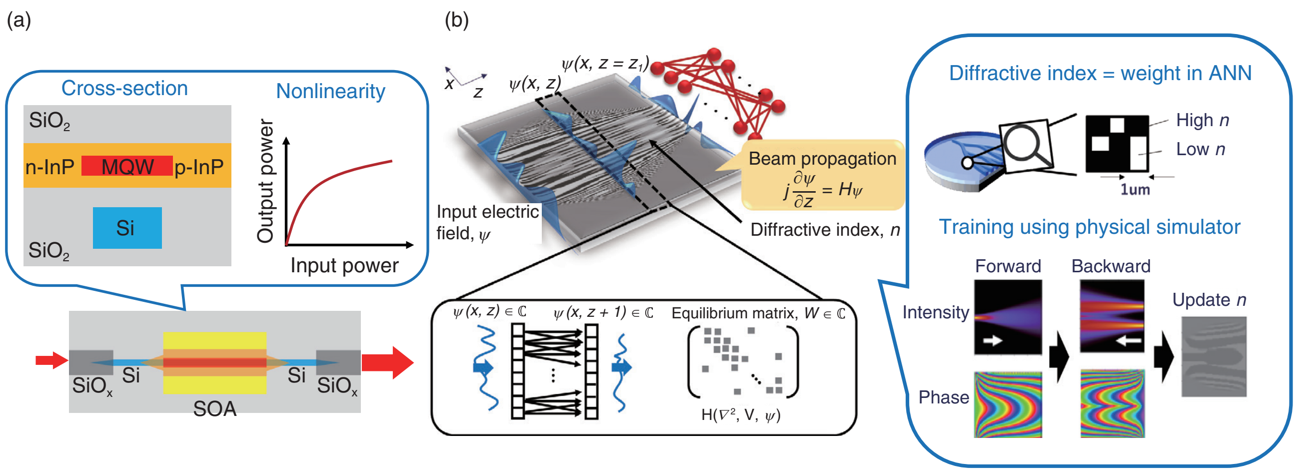
Fig. 3. (a) Application of photonic RC for coherent fiber communication. (b) FPGA-assisted photonic RC platform toward general AI application.

the optical system under training. As the training time is determined by forward propagation in RC, it can be accelerated using photonics. Thus, we focused on this configuration at the first stage of photonic implementation of an ANN.

Figure 2(b) shows our previously proposed device architecture for photonic RC [5]. In the input optical circuit (left side in figure), the optical signal is weighted along the time and space directions, which emulate the input layer of RC. In the circuit for the reservoir layer (right side in figure), a ring-shaped optical cavity array represents a recursive coupling of neurons, emulating the reservoir layer of RC. The output signals from the reservoir optics are converted to an electric signal by using a photodetector (PD). By weighting the output signals on the electric digital circuit, we can obtain a final output signal of RC. We implemented our RC architecture using a silica-based optical waveguide technology called planar lightwave circuit (PLC), which was originally developed for optical telecom devices. Our PLC acts as photonic RC with 512 reservoir neurons, which is over 30 times larger than in previous on-chip photonic implementations. The PLC can execute the multiply and accumulate operations beyond 20 tera times per second for each wavelength and reach peta-scale computation speed on a single photonic chip by using wavelength division multiplexing. This value is beyond recent electronic computation. We experimentally confirmed the performance of our PLC using standard benchmark tasks such as hand-written-digit classification. We could classify hand-written-digits images with an accuracy of 91.7% and ultrafast processing speed of 17.1 ns per image. This accuracy and speed is the highest for on-chip photonic RC implementation.

3. Application of photonic RC

As one of the features of photonic computation is its high-speed processing, we believe that it is suitable for applications that can use this advantage. An example of such an application is signal processing for optical communication, as shown in **Fig. 3(a)**. In recent optical communication, the distortions of the transmitted optical signals are compensated for using a digital signal processor (DSP). Its computational costs, however, becomes an issue to increase the



InP: indium phosphide
MQW: multiple-quantum-well
SiO_2: silicon dioxide
SiO_x: silicon oxide

Fig. 4. (a) All-optical implementation of nonlinear functionality by an SOA on silicon. (b) Schematic of wave-equation-based neural network.

communication capacity. When we use the photonic ANN including RC as the signal processor for such application, we can outsource the computational costs of a DSP to the photonic processor [6]. We are also studying a method for drastically simplifying the coherent receiver configuration by using photonic RC [7].

We are also considering the application of photonic RC to more general machine learning tasks. For such application, it is important to develop the hardware/software interface between photonic RC and a standard computation device such as a central processing unit (CPU). Therefore, we built a test platform of photonic RC using a field-programmable gate array (FPGA)-based hardware interface and Python-based software stack (**Fig. 3(b)**). The user can drive the optical RC system like standard computation hardware using a standard programming language (Python/Pytorch). We have also experimentally confirmed its superior performance [8].

4. Toward improving performance of photonic RC

To further improve the processing performance of photonic RC, it is essential to improve and harness the functionalities of photonic devices. For example, nonlinear optical effects should be more positively exploited for optical implementation of neurons, while in conventional optical communication they have been intentionally suppressed due to undesirable signal distortion. However, it is difficult for silica-based PLCs to implement such nonlinear functionalities; thus, in the above-explained physical implementation, the nonlinear functionality was implemented opto-electronically, necessitating opto-electronic conversion.

Photonic devices based on III-V semiconductors, such as an optical amplifier, can be used as all-optical nonlinear elements. By heterogeneously integrating such III-V devices on silicon photonics, nonlinear activation can be implemented all-optically even on photonic integrated circuits (PICs). To this end, we used our recently developed III-V semiconductor optical amplifier (SOA) on silicon shown in **Fig. 4(a)** to implement an all-optical nonlinear reservoir. We then experimentally evaluated its processing performance via a nonlinear benchmark task, and it was shown that the obtained performance was as good as those of typical RC with optoelectronic nonlinearity [9]. On the basis of this achievement, we are considering integrating such nonlinear functionalities on PICs toward further performance improvement of photonic RC.

In addition to the optical nonlinear implementation, large-scale optical integration of neurons is essential. Although the state-of-the-art ANN requires about 10 billion weight parameters, it is currently difficult to implement such a large-scale model with an optical ANN or RC system. The scalability of a photonic ANN is basically limited by the size of optical gate element shown in Fig. 1(a). As its typical size is about 100 μm square, it is difficult to implement the large-scale state-of-the-art ANN into standard optical circuits with a realistic footprint. We previously proposed a framework that uses lightwave propagation as a neural network, as shown in **Fig. 4(b)** [10]. In this framework, we can consider the distribution of the refractive index in the optical circuit as the weight of the neural network. Since the refractive-index distribution can be controlled to 1-μm^2 pixel size, we can achieve large-scale implementation of an optical ANN and RC about 1 million times that of the conventional method. We confirmed that the performance of the proposed wave-equation-based neural network is comparable to one for the state-of-the-art ANN. By using such new processing methods, we are now developing a photonic computation platform toward future ultrafast information processing.

5. Summary

We gave an overview of recent developments in our photonic implementation of a special type of neural network called RC. By using the nature of light, photonic RC can achieve high-speed, low-power parallel computing beyond the conventional electronic processor. We also introduced its potential application and performance improvement. In spite of the attractive features of photonic computation, the re-invention of the computer using photonic technology is still not easy. We will continue to further conduct research on a future photonic computing platform by considering the entire computing system and algorithms beyond device-level approaches.

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Business Design Support Technology to Promote Digital Transformation

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Abstract

Business processes for providing services and products are becoming increasingly complicated to meet the diverse needs of customers brought on by dramatic changes in the social environment. To make improvements to these complicated processes, it is important to accurately understand and analyze business processes on the basis of comprehensive and objective data. This article introduces the business design support technology we developed that can be used immediately on-site to effectively understand and analyze the current state of business processes and the NTT technologies at the core of this technology.

Keywords: DX promotion, business analysis, operations

1. Objective understanding of business processes to promote digital transformation

Digital transformation (DX) has been attracting attention as a means of making business more efficient through digital technology. In the corporate and government sectors, there are two approaches to achieving DX in a variety of business processes. The first is system-oriented DX to increase the efficiency of business operations required to process a large volume of items with clear requirements through systemization. The other is site-oriented DX to increase the efficiency of infrequently occurring business operations with wide-ranging requirements. A typical example of site-oriented DX is robotic process automation (RPA)*1 to automate deskwork. Plans for achieving site-oriented DX are becoming common in many corporate and government operations through the use of RPA such as WinActor®*2 [1].

However, determining exactly where to apply RPA to gain effective improvements is extremely difficult regarding complicated business processes, even for veteran operators well acquainted with business operations.

The corporate and government sectors have been searching for clues to achieving business improvements by using commercially available tools in addition to conducting on-site interviews with operators, measuring work times, etc. However, techniques such as interviews and time measurements are highly subjective, and if using commercially available tools, there is a need for detailed settings and analysis support by a specialist, which makes the hurdle to adopting such tools quite high.

2. Business design support technology

To solve the problems described above, NTT Network Innovation Center has developed business design support technology on the basis of technology established by NTT Access Network Service Systems Laboratories that can be put to use immediately on-site.

*1 RPA: Generic name for software technology that automates user operations.

*2 WinActor® is a registered trademark of NTT Advanced Technology Corporation.

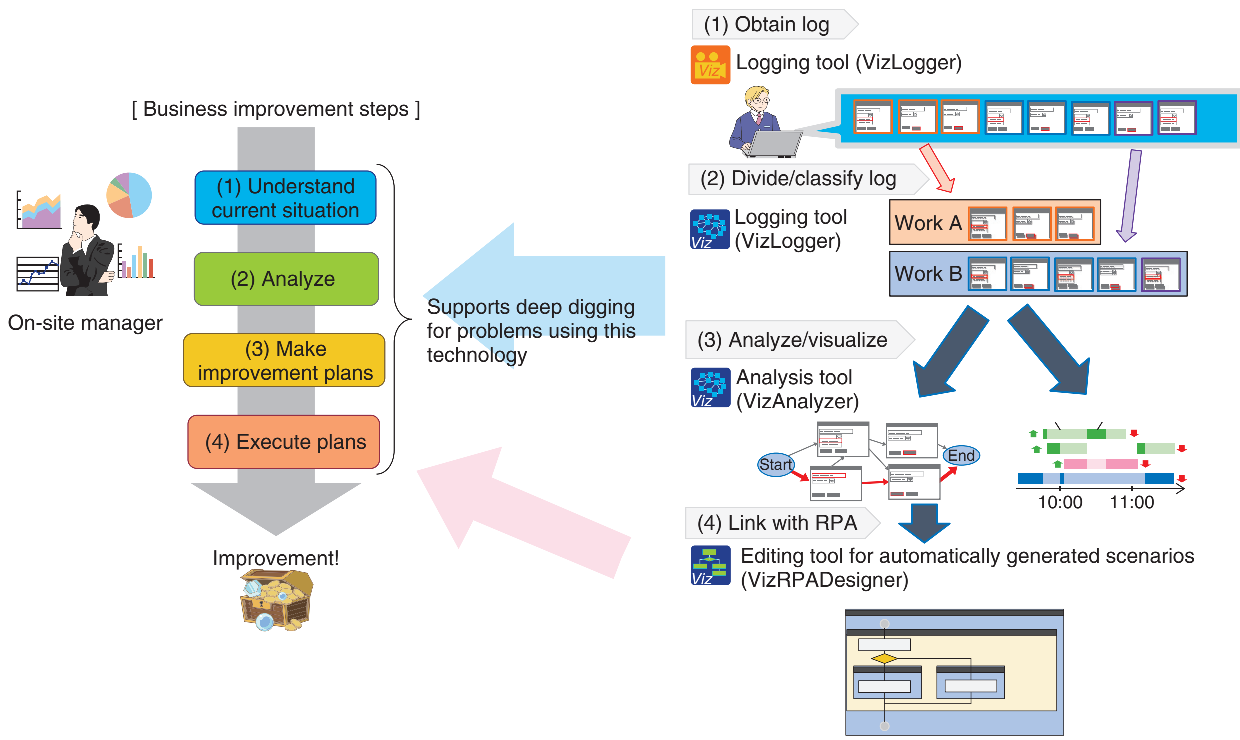


Fig. 1. Business design support technology.

Working to make business improvements requires the following steps: *understand the current situation, analyze problems and make improvement plans*, and *execute plans*.

Business design support technology provides the following tools to put the above steps into practice immediately at the user's site: a logging tool (VizLogger) that outputs the operations executed on a personal computer (PC) as a log file to support understanding of the current business situation; an analysis tool (VizAnalyzer) that classifies and visualizes the output log file and supports the analysis of problems and making of improvement plans; and a scenario editing tool (VizRPADesigner) that enables the editing of automatically generated scenarios of operational procedures from classification and visualization results and supports the generation of RPA scenario files and execution of improvement plans [2] (**Fig. 1**).

With these tools, an analyst can obtain objective and comprehensive information on the work carried out on a PC and visualize that information, enabling analysis from a variety of viewpoints. This makes it possible to extract business problems in a more effective manner than conventional techniques such as interviews and commercially available tools. These tools can be applied to not only RPA in site-oriented DX but also general business-improvement activities such as business process management*3.

2.1 Logging tool for objective and comprehensive collection of information

The logging tool automatically records operations carried out by the user to support the *understand the current situation* step.

As a platform supporting Windows 10 and Windows 7, this tool can be executed by simply opening it on the PC targeted for logging. A variety of browser environments such as Microsoft Edge*4, Google Chrome*5, Firefox*6, and Internet Explorer*7, are also supported.

*3 Business process management: The discipline of understanding the current state of business processes in a company or other organization to improve and optimize them on an ongoing basis.
*4 Microsoft Edge is a registered trademark or trademark of Microsoft Corporation in the United States and other countries.
*5 Google Chrome is a registered trademark of Google LLC.
*6 Firefox is a registered trademark of Mozilla Foundation in the United States and other countries.
*7 Internet Explorer is a registered trademark or trademark of Microsoft Corporation in the United States and other countries.

Fig. 2. Analysis tool (timeline visualization).

The logging tool detects user input operations, applications on the terminal screen, and changes in a window's status. An operation carried out by the user is obtained as an operation event. The above content can be recorded and saved as a log file (in text format) in any folder. The work screen can also be saved as a captured screen when detecting an operation event to assist the analyst in understanding business operations.

2.2 Analysis tool for making improvement plans

The analysis tool analyzes the log file stored by the logging tool using automatic work-classification technology described later to support the *analyze problems and make improvement plans* step. This tool can use three types of visualization methods to visualize the log file: timeline visualization, process visualization, and operation-sequence visualization.

(1) Timeline visualization

Timeline visualization is a visualization method for analyzing usage conditions at the window level (**Fig. 2**).

This method can display what someone is working on in a time-series manner. It can be used to intuitively discover work trends or distinctive work (work different from the norm, work taking longer than usual, etc.). This makes it possible, for example, to determine the daily operations of a certain operator and the content of that work and to compare that operator with other operators doing the same work to uncover efficient operators. In short, analyses can be conducted while switching viewpoints.

(2) Process visualization

Process visualization is a visualization method for analyzing process flow at a more detailed operation level such as clicks and keyboard input.

This method enables overall work flow to be understood through nodes (boxes) and edges (arrows). It can be used to visualize the flow of business operations, work flow, etc. It displays the captured screen and operation location at the instant of an actual operation in a node (box), which makes it even easier

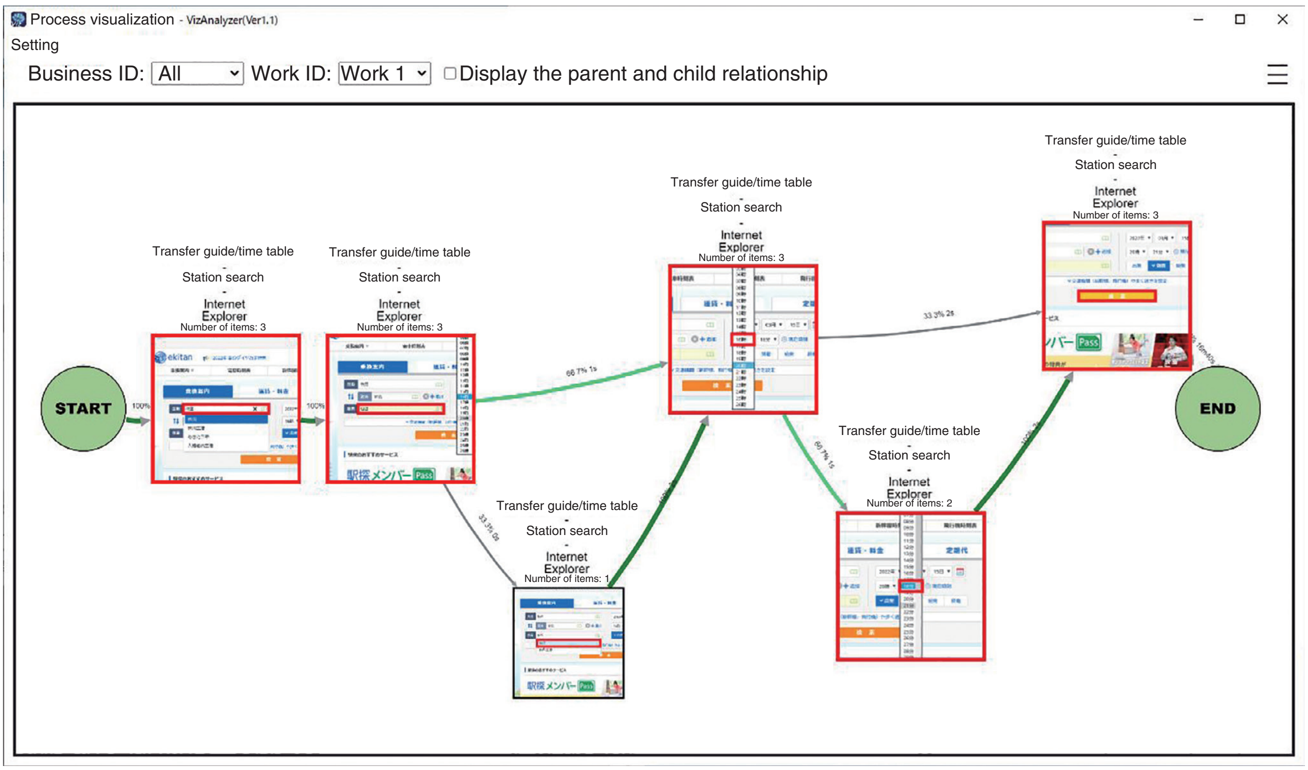


Fig. 3. Analysis tool (process visualization).

to understand the work procedure.

With this method, an analyst can compare the work procedure of a certain operator with that of other operators and analyze the differences or problems in those procedures (**Fig. 3**).

The main-flow extraction technology described later makes it possible to extract and highlight main operation flows and repeated operations from the overall work flow to support effective improvements to business.

(3) Operation-sequence visualization

Operation-sequence visualization is a visualization method for analyzing operation sequences for each specified unit (business, work, item, log, user, and date) in detail.

This method can display rectangular objects vertically for each specified display unit. It can be used for accurately tracing and analyzing individual operations or an item's operation order, which can be difficult to understand by timeline visualization or process visualization, or for making detailed studies of manual or RPA scenarios.

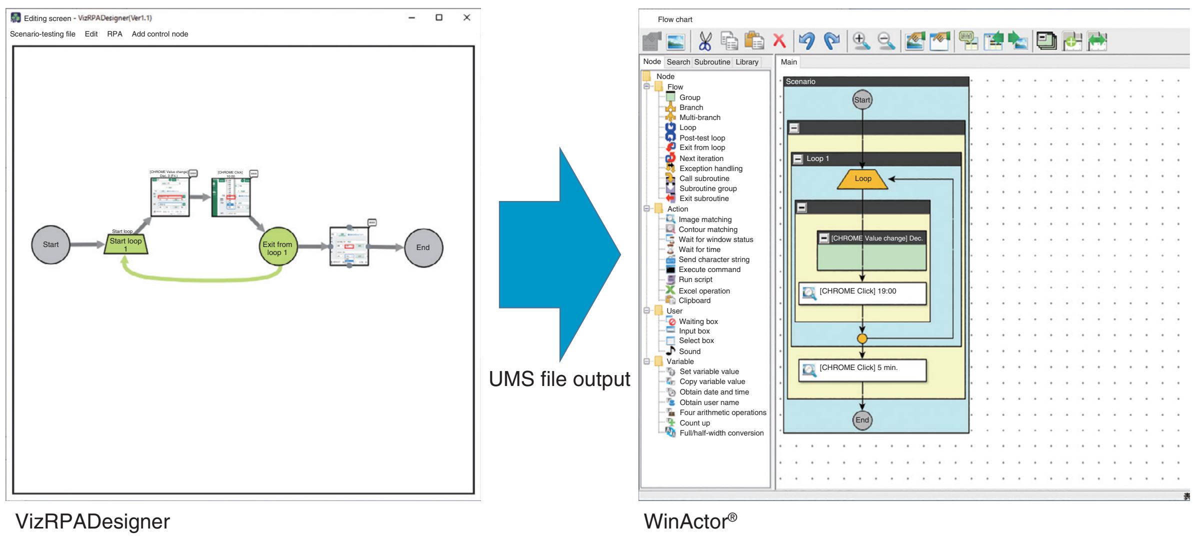
3. Editing tool for automatically generated scenarios supporting the execution of improvement plans

The editing tool for automatically generated scenarios supports the *execute plans* step by making the creation and editing of RPA scenarios on the basis of the results of the analysis tool easy to understand through visual means.

A key feature of this tool is that it can link with the analysis and visualization results of the analysis tool so that the results of the *analyze problems and make improvement plans* step can be accurately reflected in RPA scenario creation and editing. Therefore, a smooth transition can be made from *analyze problems and make improvement plans* to *execute plans* (**Fig. 4**). This tool can also automatically generate repeated operations extracted and highlighted using main-flow extraction technology in the analysis tool as RPA scenarios.

4. NTT technology features

The following describes two key NTT technologies



UMS: unified management support system

Fig. 4. Editing tool for automatically generated scenarios.

making up the core of the business design support technology [3–5].

4.1 Automatic work-classification technology

Automatic work-classification technology is incorporated in the analysis tool. It automatically classifies operation events for each type of work while absorbing fluctuations in operations that may occur such as re-ordering, reworking, and interruptions (**Fig. 5**).

An operation event is recorded by associating a mouse-click or keyboard-input event with the graphical-user-interface component (button, textbox, etc.) targeted by that operation. It corresponds, for example, to inputting the day of a business trip and pressing an approval button. With this technology, “work” is a set of operation events, and in this example, it would specifically correspond to preparing a voucher or order slip for travel expenses.

This technology focuses on the co-occurrence of consecutive operation events. It counts the number of times that operation events mutually co-occur from multiple operation events of any length and expresses each operation event as a co-occurrence vector. It also calculates the degree of relevance between operation events using cosine similarity on the basis of those co-occurrence vectors. In short, the technology can classify a log into different work groups by treating operation events with close cosine similarity as a group. A work group is defined as a set of multiple operation events corresponding to the same type of work.

With this technology, it becomes possible to appropriately classify work into work groups even if fluctuations in operations should occur, such as re-ordering, reworking, and interruptions, that are bound to occur in actual work settings.

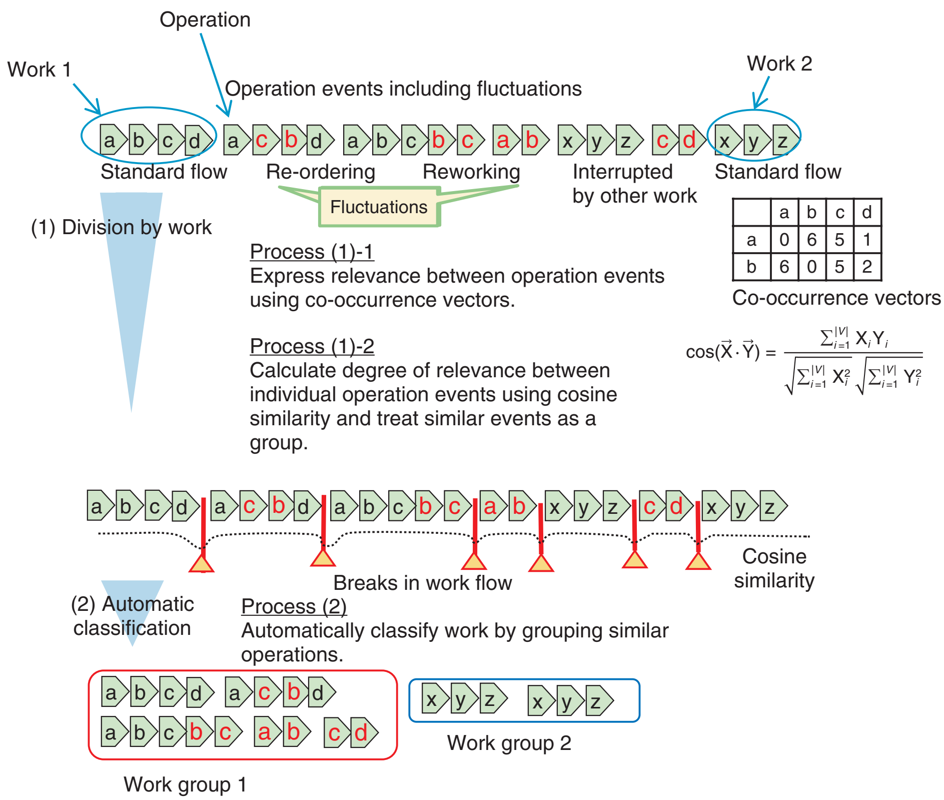
4.2 Main-flow extraction technology

Main-flow extraction technology is incorporated in process visualization of the analysis tool. It identifies main flows in which operation frequency in the processing carried out by each work group is high and for which an improvement effect can therefore be expected.

This technology applies sequence-alignment technology used in genome analysis and other fields to align multiple character strings. It can take a work group classified with the automatic work-classification technology described above and align the same operation events into the same column. The technology can also extract operation events with a high frequency of appearance in common and connect the extracted operation events in a time series, thus identifying a main flow with a high improvement effect (**Fig. 6**).

5. Future work

Our business design support technology provides tools that can support the steps of *understand the*



	a	b	c	d
a	0	6	5	1
b	6	0	5	2

$$\cos(\vec{X} \cdot \vec{Y}) = \frac{\sum_{i=1}^{|V|} X_i Y_i}{\sqrt{\sum_{i=1}^{|V|} X_i^2}\sqrt{\sum_{i=1}^{|V|} Y_i^2}}$$

Fig. 5. Automatic work-classification technology.

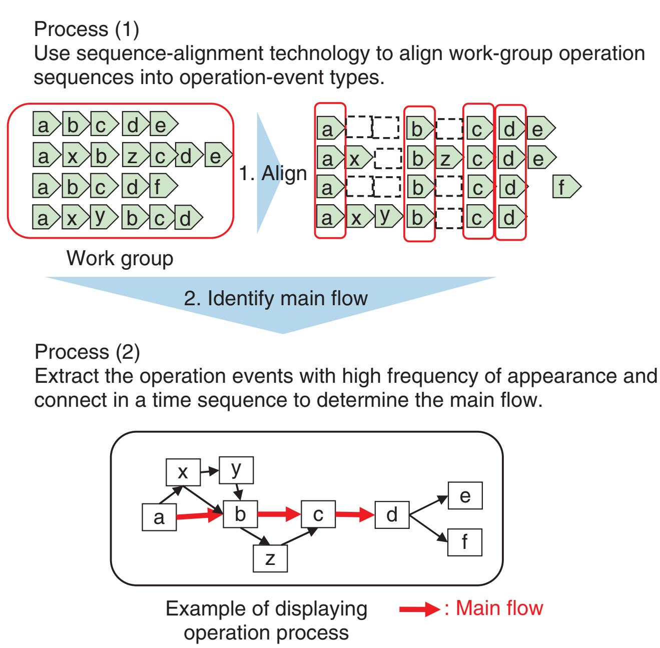


Fig. 6. Main-flow extraction technology.

current situation, analyze problems and make improvement plans, and *execute plans*. The commercial development of this technology has been completed, making it available for use in a variety of sites and settings. Going forward, we plan to promote its application in actual business operations through its deployment in the private sector and develop it into a business for more generalized markets.

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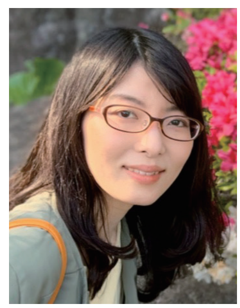

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Report on WTSA-20 (World Telecommunication Standardization Assembly)

Kazuhisa Yamagishi, Yoshinori Goto, Kazuhiro Takaya, and Noriyuki Araki

Abstract

Due to the impact of COVID-19, the World Telecommunication Standardization Assembly (WTSA-20), which was scheduled to be held in 2020, was held locally and online in Geneva, Switzerland, from March 1 to 9, 2022. This article provides an overview of WTSA-20 and the main deliberations.

Keywords: WTSA, ITU-T, Study Group

1. Position of WTSA

The World Telecommunication Standardization Assembly (WTSA) is a general assembly of the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T), which meets once every four years. The Plenipotentiary Conference makes decisions for the ITU as a whole, as shown in **Fig. 1**. As shown in **Fig. 2**, there are five committees (COM1–5) under the Plenary session (PL), which is responsible for decision-making as the General Assembly. Under COM3 and COM4, there are two working groups (WG3A, WG3B, WG4A, and WG4B) for detailed discussions. Since each committee has limited time for deliberations, ad-hoc meetings are held as needed for additional discussions, and drafting meetings are held as needed to revise resolutions. In WTSA-20, chairs and vice-chairs were elected, as shown in Fig. 2, and the PL vice-chair and COM2 vice-chair were elected from Japan.

In addition to deliberating on resolutions that establish guidelines such as ITU-T activities and working methods, WTSA deliberates on the reorganization of Study Groups (SGs) and elects chairs and vice-chairs of the Telecommunication Standardization Advisory Group (TSAG) and WTSA's committees. Many discussions at WTSA are related to policy issues and the management policies of the organization, unlike SG meetings. Therefore, a large number of government officials participate in WTSA. The participation of the private sector also plays an important role, as individual deliberations include technical content. WTSA has six regions: Asia-Pacific Telecommunity (APT), European Conference of Postal and Telecommunications Administrations (CEPT), Inter-American Telecommunications Commission (CITEL), African Telecommunications Union (ATU), Council of Arab Ministers of Telecommunication and Information represented by the Secretariat-General of the League of Arab States (LAS), and Regional Commonwealth in the field of Communications (RCC).

2. Impact of COVID-19 on WTSA-20

WTSA-20 was originally scheduled to be held in Hyderabad, India, but was repeatedly postponed due to the global pandemic (COVID-19) starting in early 2020, and was finally held as a hybrid local and online meeting in Geneva, Switzerland.

In March 2022, the effects of the global pandemic had not subsided, and many companies placed travel restrictions on participants, forcing many to abandon their on-site participation. The conference was held

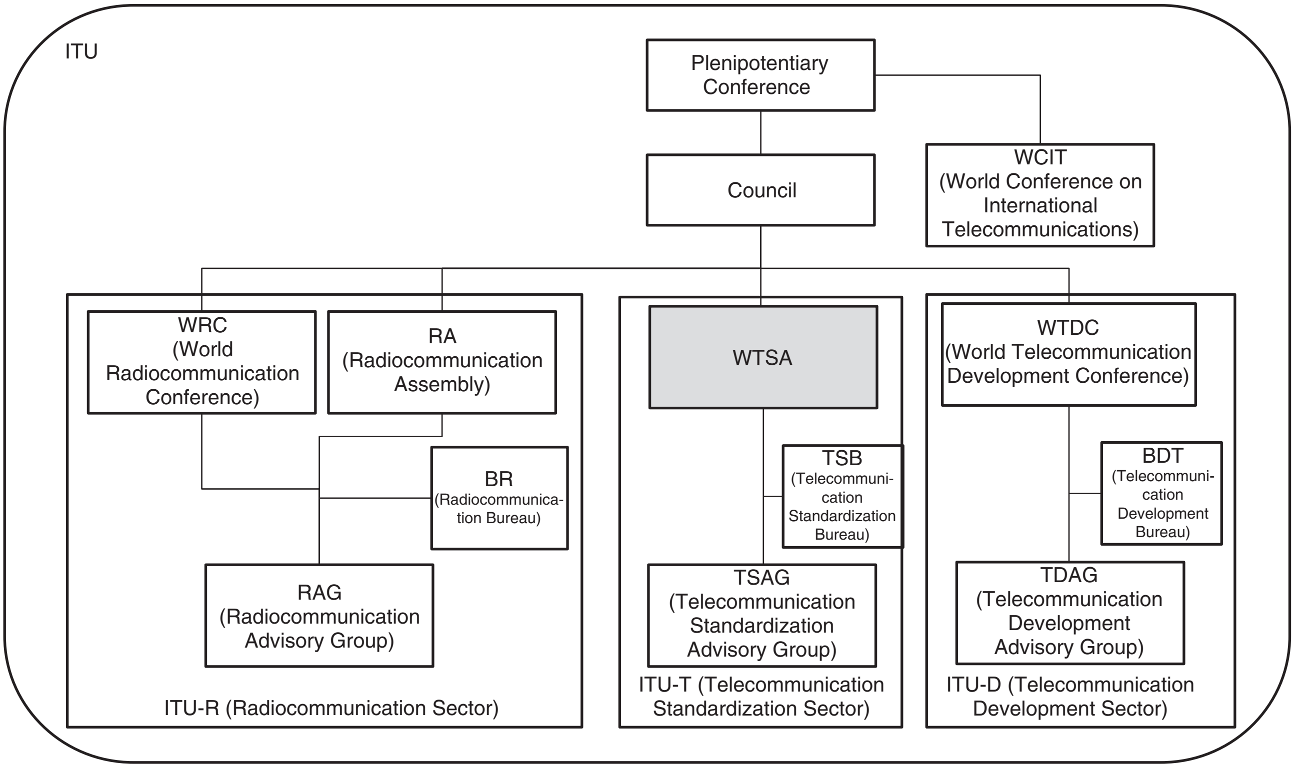

Fig. 1. Relationship between ITU and WTSA.

under unusual circumstances, as travelers were required to be vaccinated in advance, undergo PCR (polymerase chain reaction) testing, and wear masks at the venue (**Photos 1** and **2**).

During deliberations, with the exception of some discussions, online participation was made possible, allowing for remote participation. The disciplined behavior of the participants allowed us to complete the deliberations of WTSA-20 without any major problems. WTSA-24 has been announced to be hosted by India.

3. SG reorganization

SG reorganization is an important deliberation item handled by WTSA. However, as WTSA-20 was postponed due to COVID-19, it was agreed to basically maintain the SG structure for the 2017–2020 study period, and its operation is already underway from 2021. There was not much discussion and the SG structure was approved in Resolution 2 (ITU Telecommunication Standardization Sector study group responsibility and mandates). In Resolution 2, it was added that SG11 and SG17 should cooperate in security-related studies, and other minor revisions were made and approved. The Question proposed by each SG was also approved. The new study period was successfully started.

4. Election of chairs and vice-chairs

Although the appointment of chairs and vice-chairs was provided in Resolution 35, the new Resolution 208 (Appointment and maximum term of office for chairmen and vice-chairmen of the ITU) was approved at the 2018 ITU Plenipotentiary Conference (PP-18). Therefore, Resolution 35 was suppressed. PP Resolution 208 includes a provision that each SG should have no more than three vice-chairs from each region to ensure regional balance. The chairs and vice-chairs elected by WTSA-20 in accordance with PP Resolution 208 are listed in **Table 1** (* in the table indicates a second term). New chairs were elected in TSAG, SG3, 5, 11, 12, 13, 15, 17, and 20. Regional balance was emphasized in the selection of chairs, with the exception of Japan (SG9 and SG13) and Korea (SG17 and SG20), which elected two chairs, and no other country elected more than

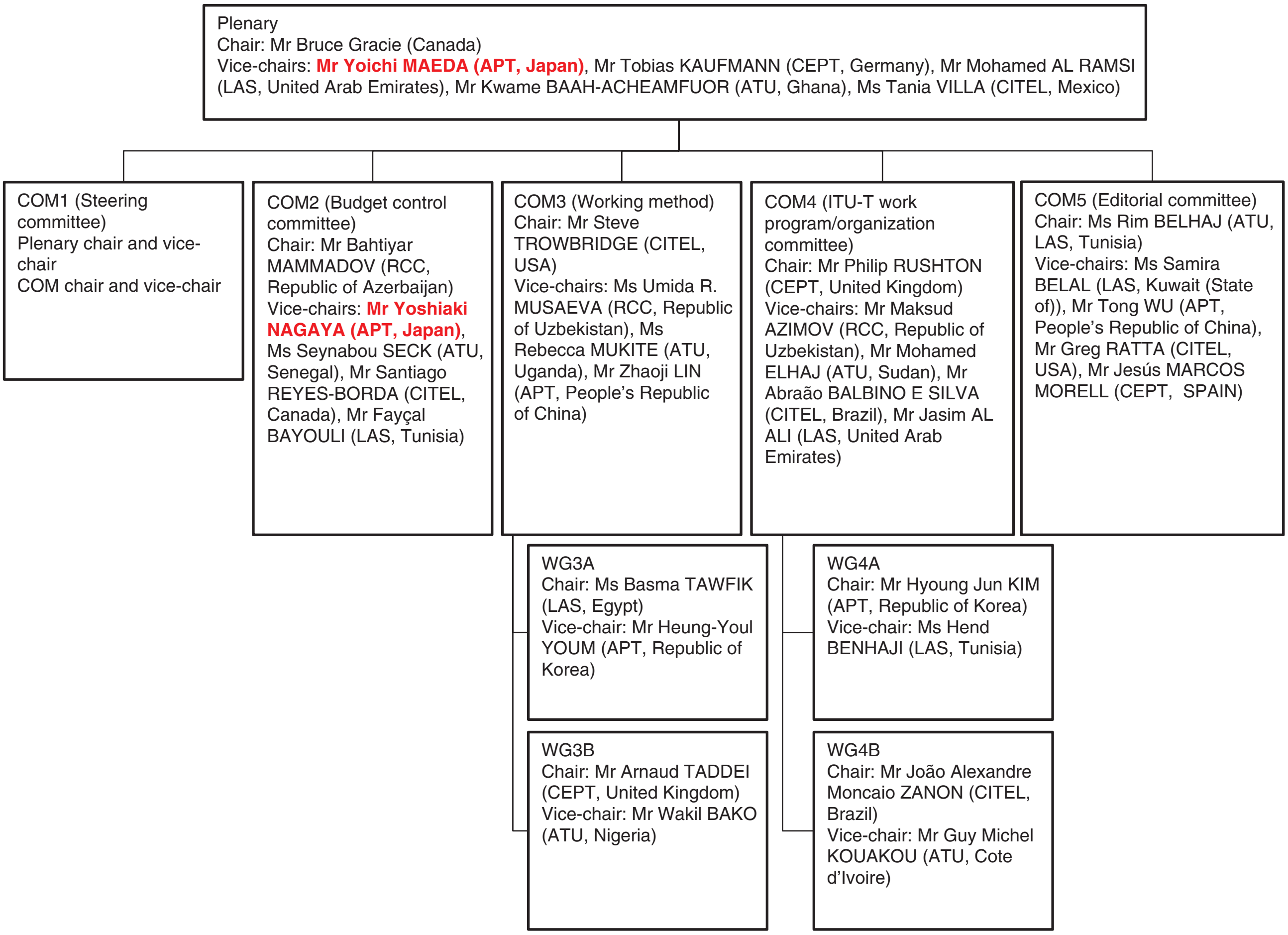

Fig. 2. Structure of WTSA-20.

Photo 1. International Conference Center Geneva.

Photo 2. Plenary of WTSA-20.

Table 1. Chairs and vice-chairs.

SG	Chairs	Vice-chairs
TSAG	Mr Abdurahma AL HASSAN (Saudi Arabia)	10 incl. Ms Miho NAGANUMA (NEC, Japan)
SG2	Mr Philip Mark RUSHTON (United Kingdom)*	9
SG3	Mr Ahmed SAID (Egypt)	12 incl. Ms Eriko HONDO (KDDI, Japan)
SG5	Mr Dominique WÜRGES (France)	9 incl. Mr Kazuhiro TAKAYA (NTT, Japan)*
SG9	Mr Satoshi MIYAJI (KDDI, Japan)*	4
SG11	Mr Sh. Ritu Ranjan MITTAR (India)	9
SG12	Ms Tania VILLA TRAPALA (Mexico)	11 incl. Mr Kazuhisa YAMAGISHI (NTT, Japan)
SG13	Mr Kazunori TANIKAWA (NICT, Japan)	13
SG15	Mr Glenn Wilson PARSONS (Canada)	7
SG16	Mr Zhong (Noah) LUO (China (P.R.))*	8 incl. Mr Hideki YAMAMOTO (OKI, Japan)*
SG17	Mr Heung Youl YOUM (Korea (Rep. of))	13 incl. Mr Yutaka MIYAKE (KDDI, Japan)*
SG20	Mr Hyoung Jun KIM (Korea (Rep. of))	11 incl. Mr Toru YAMADA (NEC, Japan)

* indicates a second term.

two. Seven vice-chairs were elected from Japan including two from NTT.

5. Major resolutions discussed at WTSA-20

WTSA-20 approved two new resolutions and suppressed four resolutions (Resolutions 35, 45, 59, and 66). Other resolutions were approved with revisions or no changes. The following is a summary of the main deliberations.

5.1 Resolutions 72/73/79

In response to the progress in wireless communication services such as the 5th-generation mobile communication system (5G), and the growing concern about climate change, the committee discussed the proposed revisions to human exposure to electromagnetic fields (Resolution 72), climate change (Resolution 73), and the circular economy (Resolution 79).

For Resolution 72 (Measurement and assessment concerns related to human exposure to electromagnetic fields), all regions (APT, CEPT, CITEL, ATU, LAS, RCC) proposed revisions. At COM4, the proposals from each region were compiled into a Working Document for ad-hoc discussion. The first of the proposed revisions was to rationalize the content of the description in accordance with the rationalization guidance approved at PP-18, and the second was to comply with the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines (revised in March 2020), which had been revised in anticipation of the use of new frequency bands in the 5G mobile network. The third was support for developing countries. The ad-hoc meeting agreed to update and delete redundant parts of the preamble and add and update the content such as promotion of ITU-T recommendations referring to the ICNIRP guidelines and support for developing countries.

For Resolution 73 (Information and communication technologies, environment, and climate change), five regions other than LAS proposed revisions, which were discussed in an ad-hoc meeting. There were two main points of revision: streamlining the description and adding the circular economy to the scope. The ad-hoc meeting reflected the proposals to remove redundant parts, add the circular economy to climate-change measures, clarify the various conditions (geographical, industrial structure, etc.) and challenges faced by developing countries, and add ecosystem monitoring, which was proposed by APT.

For Resolution 79 (The role of telecommunications/information and communication technologies in handling and controlling e-waste from telecommunication and information technology equipment and methods of treating it), ATU and APT submitted a proposal for revision, and an informal drafting group edited the draft. In addition to updating the description, it was agreed to add a section on regulations against counterfeiting of electronic waste and the importance of sustainable management.

5.2 New resolution on considering reorganization of SG structure

As mentioned in the previous section, it was agreed that the SG structure for the next study period will maintain the structure of the 2017–2020 study period, and that the reorganization of the SG structure in Resolution 2 will be implemented at WTSA-24. Prior to this, TSAG has been studying the analysis of evaluation indicators for the optimal allocation of the SG structure, and an action plan for the restructuring analysis was agreed upon at the TSAG meeting held in January 2022. This action plan aims for a thorough review of potential restructuring options for ITU-T based on the empirical analysis and was input by TSAG to WTSA-20 with a view to approving the proposed SG restructuring at WTSA-24. A new resolution on the consideration of ITU-T restructuring for the purpose of implementing this action plan on the analysis of the ITU-T SG restructuring prepared by TSAG and for the TSAG to provide each SG with a progress report on the restructuring analysis and submit a report with recommendations for consideration at the next WTSA-24 was proposed. The draft proposal (Consideration of organizational reform of the ITU Telecommunication Standardization Sector study group) was approved.

5.3 New resolution on pandemics

Due to the impact of COVID-19, proposals were made regarding global pandemics and remote participation.

First, APT, LAS, and ATU proposed and drafted a new resolution on the role of telecommunications and information and communication technology (ICT) in mitigating global pandemics. The new draft resolution was agreed upon in an ad-hoc meeting on the basis of three proposals, but the United States proposed that the new resolution should be reported at the next Plenipotentiary Conference (PP-22) since the issue of a global pandemic is not an ITU-T issue alone and to inform the Radiocommunication Bureau (BR) and the Telecommunication Development Bureau (BDT) to avoid duplication of activities. The action was approved.

Second, a new resolution on the position of face-to-face and remote participation was proposed because of the increase in remote participation due to COVID-19. However, since there are issues such as the inability to give voting rights to remote participants, the new resolution could not be agreed upon and was tabled due to the need for further discussion.

5.4 New resolution on artificial intelligence

LAS proposed and drafted a new resolution on artificial intelligence (AI) technology, as it plays an important role in telecommunications and ICT. However, the following issues were raised during the drafting process: (1) Many SGs and Focus Groups in ITU-T are already discussing AI-based technologies, and (2) the description of machine learning is included in Resolution 2. Therefore, it was proposed by the United States, Europe, and Japan that a new resolution not be drafted. Discussions were unable to reach an agreement on a new resolution, and it was decided to drop it.

5.5 New resolution on smart cables

CEPT proposed a new resolution because smart cables are useful for detecting natural disasters such as tsunamis and earthquakes, as well as climate change. However, the United States and Japan raised the issue that it is not appropriate to establish resolutions on individual technologies. Since the importance of the technology was recognized, it was proposed to continue its consideration in SG15. Discussions were parallel, and it was not possible to agree on a new resolution. However, the importance of the Joint Task Force on SMART cable systems was recognized and WTSA action was approved to avoid duplicate discussions on smart cables in cooperation with other standardization organizations.

6. Future developments

At WTSA-20, developed and developing countries could not reach an agreement on AI and other issues. Many developing countries proposed resolutions calling for ITU-T to solve their own problems, while developed countries proposed avoiding the inclusion of specific problems in resolutions. This trend is expected to continue. However, cooperation between developed and developing countries has resulted in the revision of many resolutions, making the policy more suitable for the times.

NTT has secured two vice-chair positions and will continue to work on future activities related to telecommunications and ICT in accordance with the policies of the approved resolutions.

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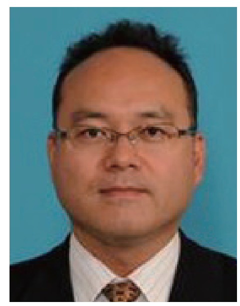

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Development of the Hikari Denwa Fault-isolation Tool for Voice Over IP Services

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Abstract

Internet Protocol (IP)-based communication systems have become more sophisticated, and the details/causes of problems are becoming more complex and diverse. This article introduces a tool developed by the Technical Assistance and Support Center, NTT EAST that is efficient in identifying the faults in voice over IP services and connected equipment. This is the seventy-first article in a series on telecommunication technologies.

Keywords: voice over IP service, packet capture, fault-isolation tool

1. Introduction

The Technical Assistance and Support Center (TASC), NTT EAST provides technical support to solve highly technical problems, the causes of which are difficult to identify. The Network Interface Engineering Group of TASC provides technical support for telecommunication services such as public switched telephone networks and leased lines, broadband internet access services called FLET'S HIKARI NEXT, etc., closed network connections using virtual private networks, Internet Protocol (IP)-based data communications, and voice over IP services, as well as terminal equipment connected to these lines.

Fixed telephone services have recently evolved and provide high-value-added services such as cloud-based private branch exchange (PBX) or the use of smartphones as PBX extensions. As such services have become more sophisticated, the details/causes of communication problems are also becoming more complex and diverse. This article introduces a tool developed by TASC that efficiently identifies the faults in voice over IP services such as Hikari Denwa.

2. Background and initiatives concerning problems with voice over IP services

Conventionally, when a trouble occurs in a voice over IP service, the fault point can be isolated by checking the status of the equipment, measuring the optical power of the communication signal, or replacing that equipment with alternative equipment. However, as networks of enterprise customers have become larger and more complex and the amount of equipment has increased, the time required to identify the cause of problems has increased. Detailed analysis is also required when customers report problems with the quality of voice over IP services, such as voices being interrupted or heard in one direction only (one-way calls).

To speed up fault isolation and identify the causes of quality problems, it is effective to capture packets between equipment and analyze them. For example, the packet-data flow from the optical network unit (ONU), which terminates the optical signal to the Hikari Denwa router (which enables voice services), telephones, etc., includes the voice data as Real Time Protocol (RTP) packets that contain the sequence

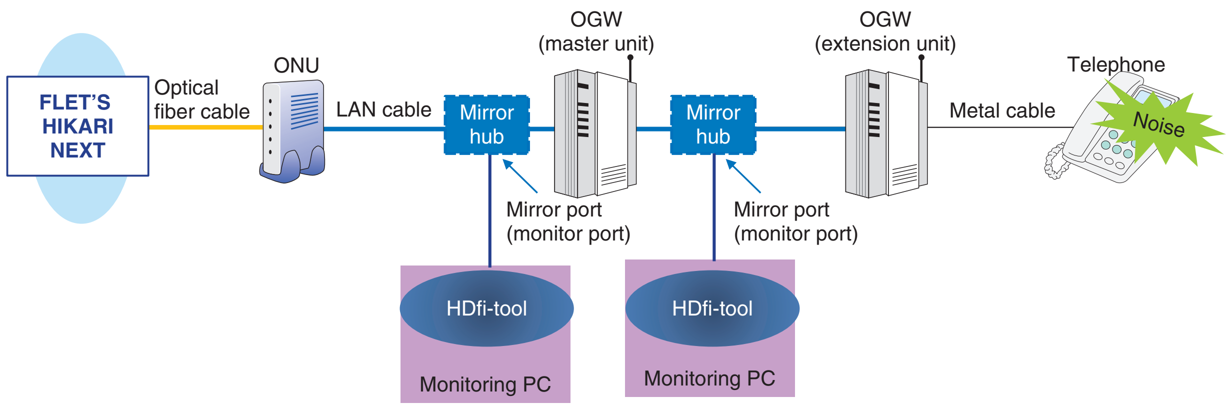

Fig. 1. Configuration diagram for isolating a fault by using HDfi-tool.

number. It is possible to identify the equipment causing the problem through analysis of the sequence number of packets or voice data.

However, it is necessary to install equipment to capture packets on site, and such packet analysis requires a high level of skill to understand and analyze the network sequence. Therefore, we developed a tool that enables on-site maintenance personnel to check the analysis results and quickly and easily identify the equipment and sections where anomalies are suspected to exist.

3. Hikari Denwa fault-isolation tool

3.1 Overview

The Hikari Denwa fault-isolation tool (hereafter, "HDfi-tool") is software that enables users to check the real-time call status and statistical analysis result of voice data on IP packets. It can operate on a personal computer (PC) or tablet PC that runs on the Windows operating system and has a wired local area network (LAN) interface. As shown in **Fig. 1**, the packet-capture function of HDfi-tool uses a general switching hub with a mirror function (hereafter, "mirror hub") or network tapping device (TAP) to interrupt a section of the LAN cable between equipment and analyze the data collected from each section.

Process flows for isolating a fault by using HDfi-tool are shown in **Fig. 2** and compared with those of the conventional method of replacing failed equipment with alternative equipment. To check the condition of voice packets by using HDfi-tool, the mirror hub is inserted between equipment; no need to change equipment (ONU or office gateway (OGW)) and no need for reconfiguration. In other words, the failed equipment can be identified through a simple operation, such as backing up the configurations and reconfiguration, backing up the reconfiguration process, that only needs to be done once to identify the cause of the fault. Therefore, the fault-isolation process is significantly shortened.

3.2 Functions and measurement procedure

HDfi-tool analyzes the Session Initiation Protocol (SIP) sequence of Hikari Denwa from packet data between equipment and automatically detects and indicates the existence of calls and their anomalies. The packet data contain telephone numbers of the outgoing and incoming terminals, and voice quality can be evaluated. It is possible to determine that a call is busy from the packet sequence and measure the indexes that affect communication quality such as packet loss and delay. HDfi-tool offers two modes of analysis: real-time analysis and statistical analysis. The packet-capture procedure is introduced and each function is explained in detail as follows.

3.2.1 Procedure

The process from packet capture to data analysis using HDfi-tool for the hypothetical configuration shown in Fig. 1 is as follows.

1) Insert the mirror hub between equipment at the point to be analyzed.
2) Connect the LAN cable from the mirror port of the hub to the analysis (monitor) PC and start HDfi-tool.
3) When a phone call is detected, the call-list table shows the call start time, telephone number, etc. (**Fig. 3**).
4) On the call-list table (3), click the target call for which the voice status is to be checked to display

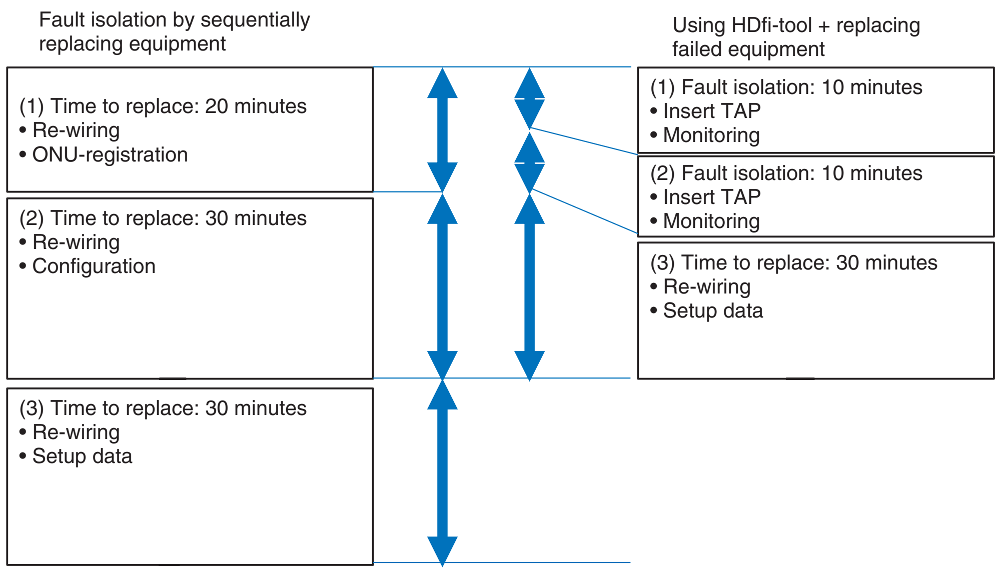

Fig. 2. Process flows of fault isolation with conventional method and using HDfi-tool.

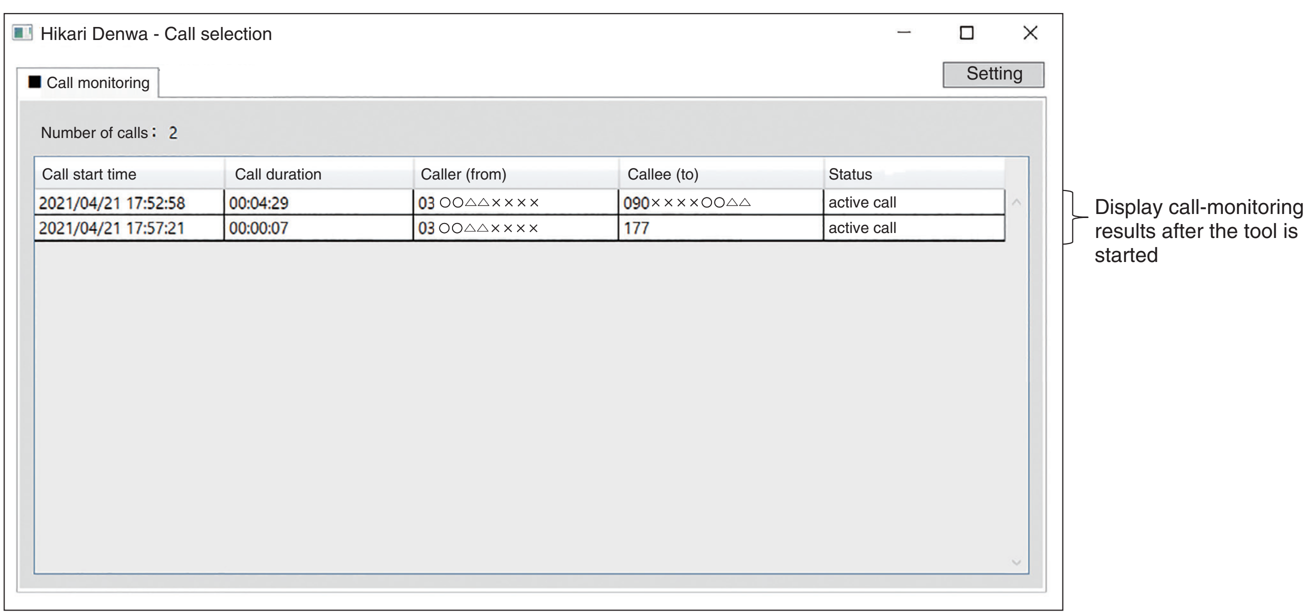

Fig. 3. Call-list table (after a call starts).

call details and statistics (**Fig. 4**).

5) Determine whether an anomaly call exists in accordance with the content shown in the table.

3.2.2 Details of functions

1) Real-time-analysis function

The real-time-analysis function displays the voice-packet conditions of the current call flowing through the Hikari Denwa line by analyzing the RTP packets flowing in the LAN-cable section. The call-list table is shown in Fig. 3. It displays start time, call duration, caller, callee, status of incoming and outgoing calls, and total number of simultaneous calls. It is possible to see if the maximum number of calls has been reached.

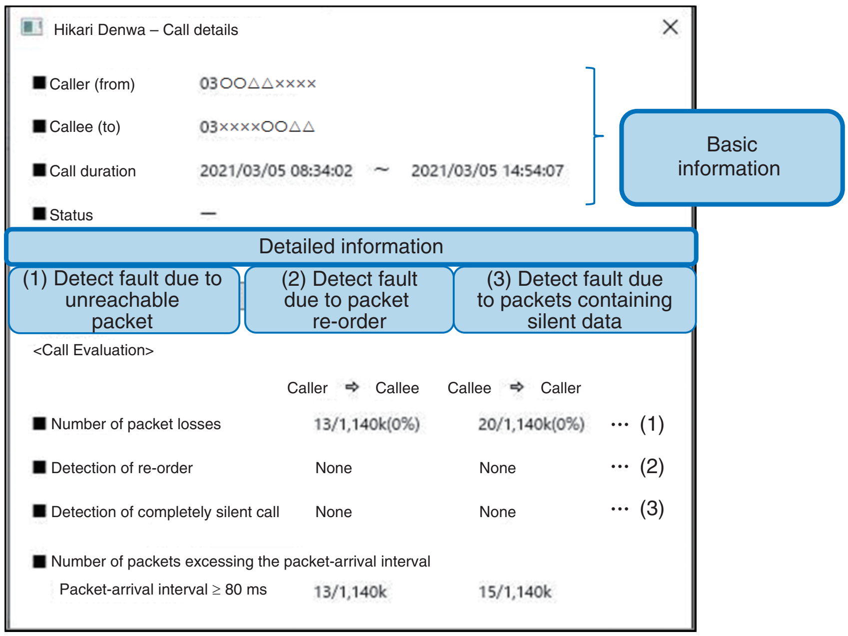

Fig. 4. Call-details window.

2) Statistical-information-analysis function

When a call is selected from the call list in the real-time-analysis function described above, the "Call Evaluation" section displayed in the call-details window (Fig. 4) allows the user to determine the presence or absence of the following anomalies in the voice data sent via RTP.

If the "Number of packet losses" increases, it is determined that the voice data are abnormal in the section in question because the increase in packet losses may cause voice interruption or silence. The relative position of the anomaly to the section where the packets are captured can be identified since this function allows the user to recognize the direction of the lost packets.

- "Number of packets excessing the packet-arrival interval" indicates the jitter of the packet-arrival time. The number of packets with an arrival interval of 80 ms or more is displayed.
- "Detection of re-order" indicates whether RTP packets arrive in the order in which they were sent. If the arrival interval of RTP packets fluctuates or packet order is reversed due to congestion in the network, etc., voice interruption may occur.
- For "Detection of completely silent call," the voice data contained in the RTP packets are checked, and the presence or absence of packets that contain continuous silent voice data is displayed. If silent data flow continuously, a malfunction of the equipment that builds RTP packets from voice data or that of the telephone is suspected.

Conventional analysis tools can list these statistics for each packet, but using them requires a high level of analysis skills and effort, such as sequentially checking sequence numbers in a huge log or calculating delays from captured packet timestamps. HDfi-tool enables simple and quick analysis of fault factors for problems with voice over IP services, and we expect it to significantly improve the workability of fault isolation.

4. How to obtain HDfi-tool

HDfi-tool has been available for download from the TASC's website* since April 2022. We believe that HDfi-tool makes on-site investigation into the causes of problems with the Hikari Denwa service faster and easier and prevents unnecessary replacement of equipment and devices.

* Due to software platform limitations, HDfi-tool is currently offered only within the NTT Group.

5. Concluding remarks

This article introduced HDfi-tool, which was developed as one of the technical-support initiatives targeting problems with IP-based systems in the field. By acquiring and analyzing data using a variety of tools, the Network Interface Engineering Group of TASC provides technical support for the early resolution of problems with equipment, terminals, and networks. We will continue to disseminate technologies by providing technical support, developing tools, holding technical seminars, and other means.

External Awards

IPSJ Fellow

Winner: Makoto Iwamura, NTT Social Informatics Laboratories/NTT Security (Japan) KK
Date: March 28, 2022
Organization: Information Processing Society of Japan (IPSJ)

For his contribution to the development of pioneering anti-cyber-attack technologies and revitalization of the security field through industry-academia cooperation.

Specially Selected Paper

Winners: Yukako Iimura, NTT Computer and Data Science Laboratories; Shinobu Saito, NTT Computer and Data Science Laboratories
Date: April 18, 2022
Organization: IPSJ

For "Industrial Practice and Evaluation of Microtask Programming for Achieving Working Style Diversity."
Published as: Y. Iimura and S. Saito, "Industrial Practice and Evaluation of Microtask Programming for Achieving Working Style Diversity," IPSJ Journal, Vol. 63, No. 4, pp. 999–1007, Apr. 2022.

Best Paper Award

Winners: Takafumi Tanaka, NTT Network Innovation Laboratories; Seiki Kuwabara, NTT Network Innovation Laboratories/NTT Communications; Tetsuro Inui, NTT Network Innovation Laboratories
Date: May 11, 2022
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE) Communications Society

For "Demonstration of Flex Ethernet over OTN Link State Monitoring Method."
Published as: T. Tanaka, S. Kuwabara, and T. Inui, "Demonstration of Flex Ethernet over OTN Link State Monitoring Method," IEICE Trans. Commun. (JPN Edition), Vol. J103-B, No. 11, pp. 595–604, Nov. 2020.

Kenneth C. Smith Early Career Award in Microelectronics

Winner: Akira Ito, NTT Social Informatics Laboratories
Date: May 21, 2022
Organization: The Institute of Electrical and Electronics Engineers (IEEE) Computer Society, Technical Community on Multiple-Valued Logic

For "A Formal Approach to Identifying Hardware Trojans in Cryptographic Hardware."
Published as: A. Ito, R. Ueno, and N. Homma, "A Formal Approach to Identifying Hardware Trojans in Cryptographic Hardware," 2021 IEEE 51st International Symposium on Multiple-Valued Logic (ISMVL), pp. 154–159, Nur-Sultan, Kazakhstan, May 2021.

Standardization Achievement Award

Winner: Seishi Takamura, NTT Computer and Data Science Laboratories
Date: May 24, 2022
Organization: IPSJ/Information Technology Standards Commission of Japan

For his long-term contribution to the standardization activities in International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) Joint Technical Committee 1 Subcommittee 29 since 1998.

IPSJ Fellow

Winner: Seishi Takamura, NTT Computer and Data Science Laboratories
Date: June 7, 2022
Organization: IPSJ

For his achievement concerning the research and development of video coding and contribution to its standardization and dissemination.

IACR Fellow

Winner: Masayuki Abe, NTT Social Informatics Laboratories
Date: June 27, 2022
Organization: The International Association for Cryptologic Research (IACR)

For influential contributions to practical cryptosystems and for exemplary service to the IACR and the Asia-Pacific cryptography community.

Papers Published in Technical Journals and Conference Proceedings

Sumcheck-based Delegation of Quantum Computing to Rational Server

Y. Takeuchi, T. Morimae, and S. Tani

Theoretical Computer Science, Vol. 924, No. 1, pp. 46–67, April 2022.

Delegated quantum computing enables a client with weak computational power to delegate quantum computing to a remote quantum server in such a way that the integrity of the server can be efficiently verified by the client. Recently, a new model of delegated quantum computing has been proposed, namely, rational delegated quantum computing. In this model, after the client interacts with the server, the client pays a reward to the server depending on the server's messages and the client's random bits. The rational server sends messages that maximize the expected value of the reward. It is known that the classical client can delegate universal quantum computing to the rational quantum server in one round. In this paper, we propose novel one-round rational delegated quantum computing protocols by generalizing the classical rational sumcheck protocol. An advantage of our protocols is that they are gate-set independent: the construction of the previous rational protocols depends on gate sets, while our sumcheck technique can be easily realized with any local gate set (each of whose elementary gates can be specified with a polynomial number of bits). Furthermore, as with the previous protocols, our reward function satisfies natural requirements (the reward is non-negative, upper-bounded by a constant, and its maximum expected value is lower-bounded by a constant). We also discuss the reward gap. Simply speaking, the reward gap is a minimum loss on the expected value of the server's reward incurred by the server's behavior that makes the client accept an incorrect answer. The reward gap should therefore be large enough to incentivize the server to behave optimally. Although our sumcheck-based protocols have only exponentially small reward gaps as in the previous protocols, we show that a constant reward gap can be achieved if two noncommunicating but entangled rational servers are allowed. We also discuss whether a single rational server is sufficient under the (widely believed) assumption that the learning-with-errors problem is hard for polynomial-time quantum computing. Apart from these results, we show, under a certain condition, the equivalence between *rational* and *ordinary* delegated quantum computing protocols. This equivalence then serves as a basis for a reward-gap amplification method.

Rewindable Quantum Computation and Its Equivalence to Cloning and Adaptive Postselection

R. Hiromasa, A. Mizutani, Y. Takeuchi, and S. Tani

arXiv:2206.05434, June 2022.

We define rewinding operators that invert quantum measurements. Then, we define complexity classes RwBQP, CBQP, and AdPostBQP as sets of decision problems solvable by polynomial-size quantum circuits with a polynomial number of rewinding operators, cloning operators, and (adaptive) postselections, respectively. Our main result is that $\mathrm{BPP}^{\mathrm{PP}} \subseteq \mathrm{RwBQP} = \mathrm{CBQP} = \mathrm{AdPostBQP} \subseteq \mathrm{PSPACE}$. As a byproduct of this result, we show that any problem in PostBQP can be solved with only postselections of outputs whose probabilities are at least some constant. Under the strongly believed assumption that the shortest independent vectors problem cannot be efficiently solved with quantum computers, we also show that a single rewinding operator is sufficient to achieve a task that is intractable for quantum computation. In addition, we consider rewindable Clifford and instantaneous quantum polynomial time circuits.
