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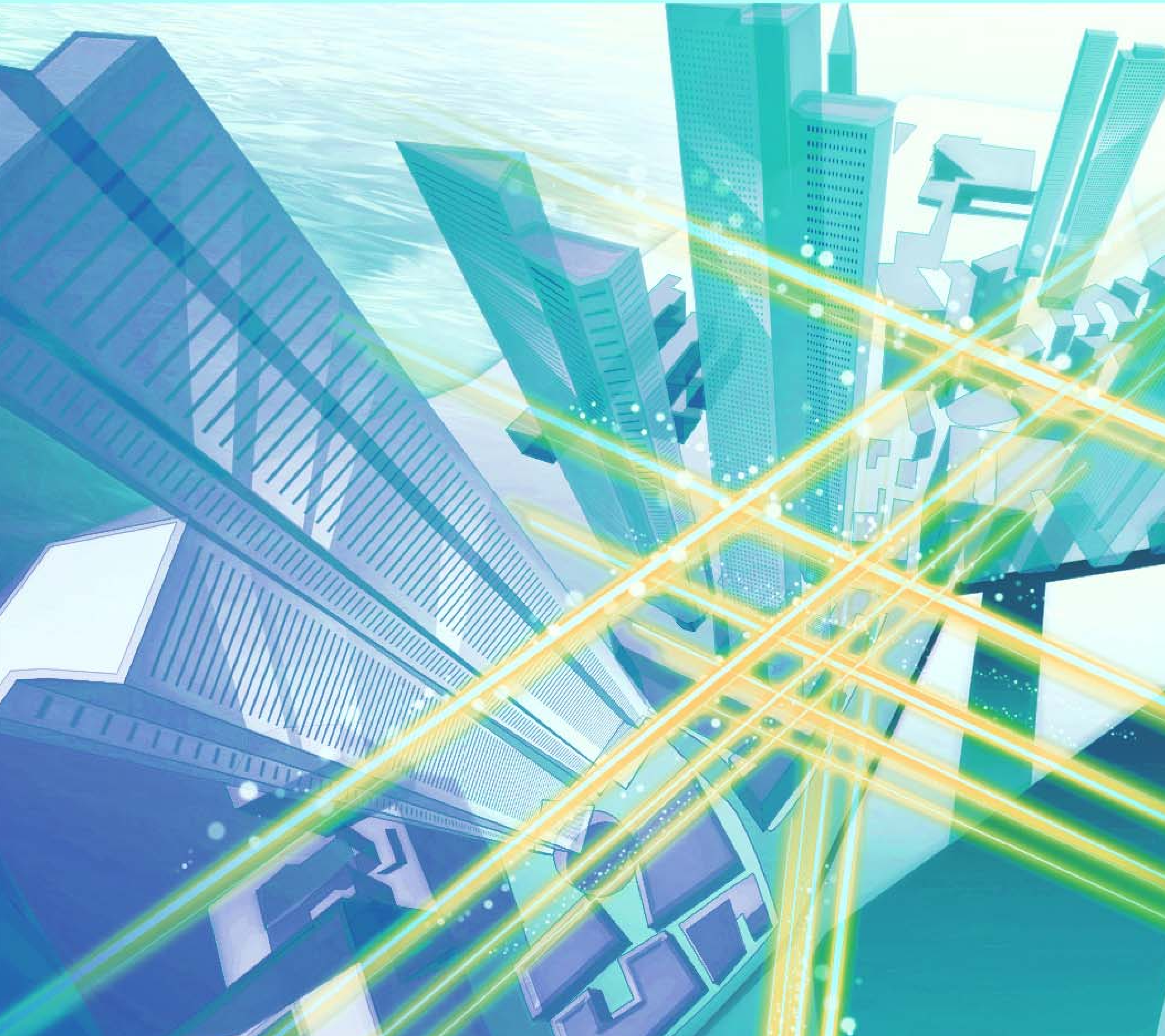

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Aiming to Attain Global No. 1 Technological Capabilities and Maximize the Value We Provide to Our Clients

Hiroshi Tomiyasu
Senior Vice President, Head of Technology and Innovation General Headquarters, NTT DATA

Abstract

NTT DATA creates new systems and value using information technology to contribute to creating a more prosperous and harmonious society. In accordance with the five strategies laid out in its medium-term management plan for FY 2022 to 2025, the company aims to establish a virtuous cycle of investment and growth and achieve business growth toward the Global 3rd Stage. Hiroshi Tomiyasu, senior vice president and head of Technology and Innovation General Headquarters, NTT DATA, is leading efforts toward this goal in terms of technology. We interviewed him about specific technology strategies and his belief as a top executive.

Keywords: system integration, technology strategy, human resources

Leading the Technology and Innovation General Headquarters

—Could you tell us about the technology strategies of NTT DATA?

NTT DATA is a global company that has grown over the past few years to employ 190,000 people worldwide. We have been striving to expand our business globally since FY 2005. In the Global 1st Stage, we increased our global coverage; in the Global 2nd Stage, we strived to establish a global brand; and in the Global 3rd Stage, we are aiming to become one of the top-five information technology (IT) service providers in the world. As the midpoint of the Global 3rd Stage, during the previous medium-term management plan for FY 2019 to 2021, we pursued profitable growth on a global scale with consistent belief and courage to change.

To accomplish the Global 3rd Stage, under the current medium-term management plan for FY 2022 to 2025, we aim to create value by connecting people with technology and build a sustainable future in unison with our clients. To achieve this aim, we are pursuing the following five strategies: (i) Capitalize on the Convergence IT & Connectivity, (ii) Strengthen Consulting with Foresight, (iii) Evolve to an Asset-based Business Model, (iv) Enhance Advanced & Development Technology, and (v) Be the Best Place to Work.

The Technology and Innovation General Headquarters, which I lead, plays the role of the headquarters for engineering teams scattered throughout Japan, the United States, and Europe. In accordance with our technology strategies for attaining global No. 1 technological capabilities and maximizing the value we provide to our clients, we are working on globally identifying and using not only the technology that can be used now but also the technology that will spread in the future through the application of advanced technology and co-creation research and development (R&D) to solve client problems. We are focusing on two of the five strategies of the medium-term management plan, Evolve to an Asset-based Business Model and Enhance Advanced & Development Technology. While identifying the technology areas to focus on, we are developing technology that will enable system development with high productivity and agility suitable for the digital age and provide that technology as global common assets. To continuously improve the value of such assets, we are also promoting the effective use of human resources with advanced technical skills.

—It is a big role to take on two of the five strategies. Evolve to an Asset-based Business Model is likely to attract a lot of attention, isn't it?

Our business model has traditionally been system integration (SI) by which we develop a computer system tailored to each client's needs. We have been engaged in sales activities through which we receive a request for proposal (RFP) from a client and develop a custom-made, one-of-a-kind system in accordance with the RFP. We will shift from this conventional SI to asset-based SI by fully demonstrating our ability to develop systems with client understanding and advanced technologies that we have cultivated thus far and our ability to support various enterprise systems and industry infrastructure to connect people, enterprises, and society.

The background behind this initiative includes two challenges we must address: securing IT human resources and quickly responding to ever-changing environments and client requests. Regarding the former challenge, expanding sales while maintaining the conventional SI business model necessitates executing many projects with considerable human resources. However, the global competition for IT talent is heating up, so it is not always possible to secure those human resources. It is therefore important to shift from custom-made system development, and we have decided to pursue a business model in which the NTT DATA Group's technologies, knowledge, and experience are consolidated into assets at the global level and effectively used in multiple regions and industries.

Regarding the latter challenge, as the use of digital technology accelerates business, the conventional SI business model cannot keep up with such speed. Accordingly, we will evolve our business model to one in which we proactively propose and disseminate our products and services by leveraging our assets so that we can acquire the business agility suited to the digital age and maximize the value we provide to our clients.

Assets can be many things, but we mean *reusable* assets such as industry and business foresight, best practices, software, and in-house tools. The Technology and Innovation General Headquarters is responsible for creating common global technology assets, and we are selecting global technology focus areas and developing industry-independent technology assets in each area. By expanding the scale of sales, increasing the number of engineers, and building an ecosystem by strengthening partner alliances in each area, we aim to acquire global No. 1 technological capabilities and accelerate our transformation to an asset-based business model by taking advantage of such capabilities.

Reorganizing R&D and technology-development activities on the basis of Emerging, Growth, and Mainstream categories

—Could you explain the other strategy, Enhance Advanced & Development Technology?

This is a key strategy for turning our technology into our business by strengthening our ability to use advanced technology to gain future competitiveness and system-development technology to improve productivity. We first divided these technologies into three categories—Emerging, Growth, and Mainstream—in accordance with the maturity level of each technology and reorganized our R&D and technology-development activities on the basis of these categories.

In the Emerging category, we will search for advanced technologies that will be available five to ten years from now and conduct co-creation R&D that examines value creation with clients by using new technologies.

In the Growth category, we will develop technologies to create growth business and technology-focus areas in three to five years, create technology assets, and conduct business-feasibility tests as well as train engineers.

In the Emerging and Growth categories, we will begin full-fledged development of our technology assets to achieve global business expansion from a technological standpoint. The Innovative Optical and Wireless Network (IOWN) is a priority theme for creating new social value, and we are collaborating with NTT laboratories, which conduct R&D on component technologies for IOWN. In particular, we are developing a common testbed so that their research results can be commercialized and delivered to our clients. We are also promoting a digital twin co-creation program for conducting co-creation R&D with our partners engaged in social innovation.

In the Mainstream category, we will develop technology assets in technology-focus areas concerning current business, unify our global strategy to expand our business in Japan, the United States, and Europe, increase delivery resources, and expand market share. The main technology-focus areas in this category include “cloud” for system development using various cloud services; “application development and management,” which pursues highly agile system development and productivity improvement by using digital technologies; “cybersecurity,” which focuses on security services on the basis of the concept of zero trust, rather than the conventional perimeter defense; and “data and intelligence,” which intends to create new business value through data analysis and data utilization by using artificial intelligence (AI).

—The reorganization of the Technology and Innovation General Headquarters seems to be a flagship initiative for the business transformation of NTT DATA.

I think it is a touchstone rather than a flagship. As I mentioned at the beginning, NTT DATA has grown into a company with 190,000 employees worldwide. This growth process involved mergers and acquisitions, and business styles of each company, business practices and business processes in each country, and characteristics and needs of clients all differ. As we standardize, and in some cases, integrate these different practices and systems and strategically establish NTT DATA's identity, we must accommodate the different needs of our clients in each region. This process will take a considerable amount of time; however, in a sense, the technologies are the same worldwide, so they are easy to unify, therefore, we unified and shared the technology strategies ahead of business practices.

Of course, some things will go wrong because it is the first time. Accordingly, we have changed our approach to business plans; that is, we implement them speedily and revise them as necessary. Specifically, we review business plans every three months with executives from each country in reference to the status of their implementation. Since we constantly monitor and undergo major revisions every three months, I do not have time to be satisfied or dissatisfied with the progress of the business plans. I work with the mindset that the repetition of working enthusiastically will lead to a job well done later.

When making this assessment, in addition to the usual indicators, one of the points to consider is whether a project is in a *busy state*. I think the work we have done to the best of our abilities while saying, "It's so tough," is probably that in which we look back on later and think, "That was interesting and fulfilling." I have had this experience myself, and I take into consideration whether the project members are engaged in the project enthusiastically.

Developing human resources with enthusiasm

—Could you tell us what is important to you as a top executive?

I entered NTT DATA in 1990 and studied image-recognition systems at the R&D department for about ten years. However, due to the company's decision to stop developing image-recognition systems in the light of the background of that time and future potential, I was transferred to a department related to financial systems.

I learned an important lesson from that experience. That is, it is important not to continue a project simply by force of habit; instead, it is necessary to have a strong conviction to withdraw or change course in a timely manner. NTT DATA is now a global company with 190,000 employees, and if we continue to work by inertia, those 190,000 employees will go in the wrong direction. That is why we share NTT DATA's clear technology strategies for global integration with engineers around the world while promoting transformation with conviction.

It is also important to have a good sense of whether a technology being developed will be accepted by clients and whether it is likely to become popular. It is necessary to develop technologies that can address issues that front-line employees found in direct communication with clients and create products that front-line employees can propose to clients while confidently saying, "We can solve your problems with this technology."

However, engineers tend to be somewhat distant from the field, thus end up developing technologies on the basis of their own ideas and proposing the results of that development to clients. Unfortunately, technologies and services developed through that process are often dismissed by clients. For these reasons, I value timely decisions taken by the front-line employees.

—I see that you value the perspective from the front line. Finally, what would you like to say to people inside and outside the company?

I strive to develop human resources with enthusiasm. As for nurturing people, it is important to have the ability to identify who they are and what kind of sense they have. That is because not everyone grows up in the same time or at the same rate. If people's growth rates differ, so will their senses. I believe that the ability of top executives is determined by whether they can give a job that matches the individuality of each employee. We always keep in mind that we need to assess the individuality of the person we want to nurture in terms of whether the job is too difficult or too easy for them.

I would like to say to our partners that global competition for talent has become increasingly fierce. The media reports on layoffs at global technology companies may lead you to believe that the IT workforce is already saturated; the reality is different. Information and communication technology is changing at a dizzying pace, and the human resources required are changing as well. Therefore, we are competing to acquire human resources who can cope with that change. Moreover, with the advent of various types of AI, it is easy to imagine that all computer systems will be replaced with AI in the future. However, it is people who are operating those systems, and computer systems and software will continue to be necessary. That is why people will continue to be important. I want to work together in taking responsibility for nurturing not only people within our company but also all our partners.

I would like to say to our clients and prospective clients that our highly skilled employees are ready to meet your needs and I hope you will choose us.

Finally, I'd like young engineers to immerse themselves in the study of technology and, as the common adage goes, "forget about eating and sleeping." The value of software and computer system technologies is determined by whether people use them, so if you have the chance, gain experience in the field while you are still young and grow as an engineer.

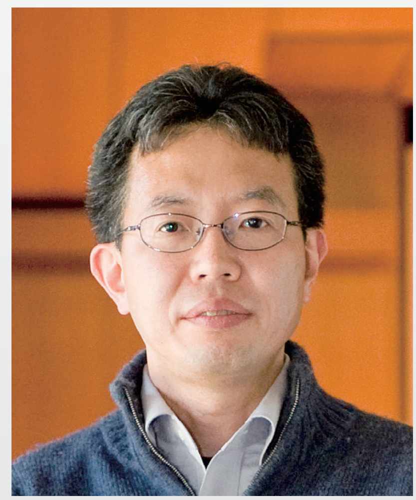
Interviewee profile

■ Career highlights

Hiroshi Tomiyasu joined NTT DATA Communications Systems Corporation (currently NTT DATA Corporation) in 1990. In his career at NTT DATA, he became general manager of the Research and Development Headquarters in 2007, head of the Center for Applied Software Engineering of Research and Development Headquarters in 2011, head of the System Architecture Department of the Infrastructure System Sector, Technology and Innovation General Headquarters in 2015, and head of the System Engineering Headquarters of the Technology and Innovation General Headquarters in 2017. He assumed his current position in June 2020.

Researchers Have a Responsibility to Create New Knowledge and Technology and Let That Responsibility Be Rewarding

Masaya Notomi
Senior Distinguished Researcher, NTT Basic Research Laboratories and Project Leader of NTT Nanophotonics Center



Abstract

NTT Nanophotonics Center is investigating photonics-electronics convergence technologies with the aim of creating low-latency and low-energy-consumption optical computing technology. As various types of photonic information processing are becoming possible, Masaya Notomi, a senior distinguished researcher at NTT Basic Research Laboratories and project leader of NTT Nanophotonics Center, is pursuing the control of optical properties of materials and device applications by using artificial nanostructures. We interviewed him about the progress of his research activities and his attitude as a researcher.

Keywords: nanophotonics, photonics-electronics convergence, topological photonics

Pursuing new phenomena and photonic processing devices by using integrated nanophotonics

—Our last interview was in 2020. Can you tell us about the progress of the research you are conducting?

Since joining NTT, I have been pursuing the discovery of new phenomena and development of photonic processing devices using integrated nanophotonics. More specifically, I have been engaged in creating new nanophotonics structures by using state-of-the-art nano/microfabrication techniques, discovering new physical phenomena manifested in those structures, and developing technologies to fabricate photonics-electronics convergence information-processing chips with ultrahigh speed and ultralow energy consumption.

Modern photonics technology is the driving force behind high-capacity information transmission such as long-distance optical-fiber communications and server-to-server communications within datacenters. Research is trending toward applying the high-speed and large-capacity properties of light to the circuits inside devices, and the ultimate form of the application

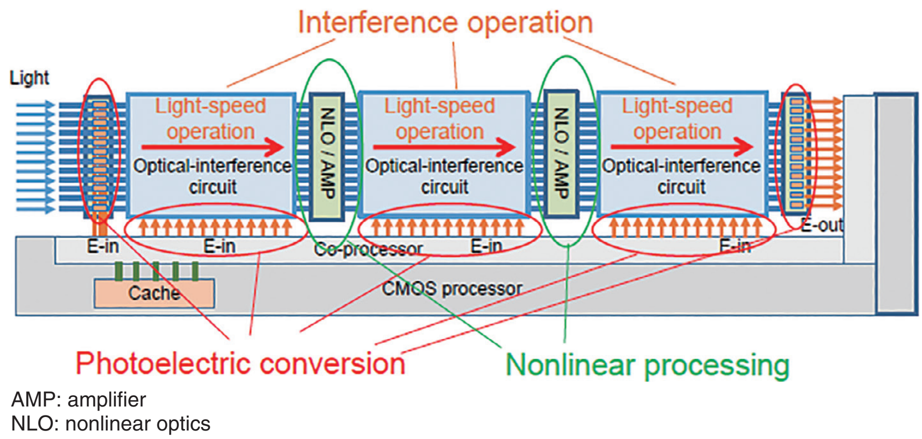


Fig. 1. Conceptual diagram of photonics-electronics convergence accelerator.

of light is the configuration of optical network circuits in computer chips and direct information processing using light. Although the creation of an optical computer has long been one of the major goals of researchers in the field of optics, in a world where complementary metal-oxide semiconductor (CMOS) electronic circuit technology is gaining prominence, the significance of using light for arithmetic processing has not been recognized in terms of ease of implementation and cost.

As the limits of miniaturization and integration of CMOS technology (the so-called "end of Moore's law") gradually approach, expectations for arithmetic processing taking advantage of the high-speed nature of light are growing. Integrated nanophotonics technology makes it possible to achieve such processing. With nanophotonics technology, highly advanced semiconductor nano/microfabrication techniques are used to create nanometer-scale structures that are the same size as (or smaller than) the wavelength of light, which enables miniaturization of devices and creation of new optical properties that would be unfeasible with conventional optical devices. An example result of the application of nanophotonics technology is a photonic crystal, which is an artificial structure in which refractive index is periodically modulated on a submicron scale. We have used this crystal to fabricate ultrasmall devices and devices with ultralow energy consumption.

Although optical arithmetic processing is anticipated, it is currently difficult to execute various general-purpose processing operations on optical circuits only. Therefore, we focused on combining the complex digital signal processing and large-capacity memory of electronic circuit technology with optical circuit technology that carries out the processing that light excels at to accelerate specific arithmetic processing operations, namely, functionalization of the optical circuit as an accelerator. In addition to digital signal processing, analog signal processing plays an important role in machine learning, which is increasingly in demand, and the value of using light in analog signal processing is being recognized. We have therefore set a goal of creating a photonics-electronics convergence accelerator that combines CMOS electronics and nanophotonics, as shown in **Fig. 1**. This accelerator will enable (i) light-speed operations exploiting optical propagation (especially optical interference), (ii) improvement in the efficiency of photoelectric conversion and digital-to-analog conversion through the fusion of photonics and electronics at the arithmetic processing level, and (iii) generation of effective nonlinear optical properties by using optical transistor technology.

—You are involved in research with high academic and social expectations, right?

Under the title of "Development of a photonics-electronics convergence computing infrastructure utilizing spatial, temporal, and wavelength degrees of freedom," our research on developing a low-latency and low-energy-consumption computing accelerator was selected as a research project of the Japan Science and Technology Agency's Core Research for Evolutionary Science and Technology (JST-CREST) in 2021 in conjunction with the National Institute of Advanced Industrial Science and Technology (AIST), Nagoya University, Kyoto University, and Kyushu University. In this research project, we are pursuing photonics-electronics convergence information processing, which combines transmission using optical technology with CMOS technology to enable high-speed signal processing that takes advantage of the properties of light. On the basis of the photonics-electronics convergence technology to be implemented around 2030, which is the commercialization target of the Innovative Optical and Wireless Network (IOWN), we are considering the application of this information processing to a computer system that uses optical signals for certain information-processing operations in the chip.

Two key points must be addressed in this research project. The first is to solve the problem regarding the integration of CMOS circuits and optical circuits. The key to this integration is to create high-density optical-electronic interfaces by reducing the size and energy consumption of electrical-to-optical converters (EO conversion), such as optical modulators, and optical-to-electrical converters (OE conversion), such as photodetectors. We have built the world's first femtofarad-level-capacitance photoelectric conversion device using photonic-crystal technology and demonstrated that by suppressing capacitance, photoelectric conversion is possible with very little energy consumption. I believe that this technology will enable the first photonics-electronics convergence computing system that seamlessly fuses light and electricity to achieve both high computing power and low power consumption.

Another important aspect of this highly efficient photoelectric conversion technology is the ability to add new functions to light. By using integrated nanophotonics technology, we developed a nanophotodetector-nanomodulator integrated device (OEO-conversion device), a photonics-electronics-converged device with both OE conversion and EO conversion functions and is very small (10×15 μm^2). We have succeeded in operating this device as an optical transistor. Since optical transistors can execute nonlinear processing, which has conventionally been difficult with light, we believe this device can be used for nonlinear processing, as shown in Fig. 1, and be a key device in photonics-electronics convergence neural-network (NN) processing.

A critical step toward ultralow-latency and low-energy-consumption information processing systems

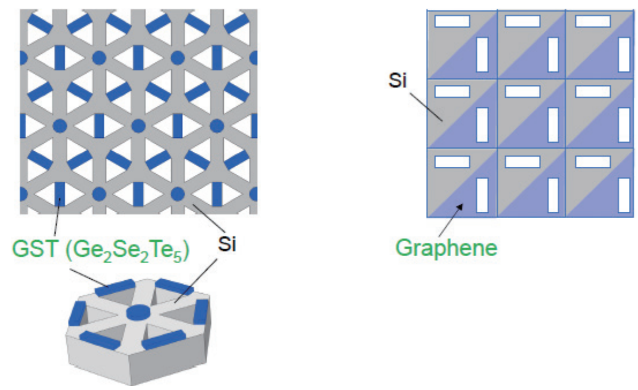
—You are achieving fantastic results. Would you tell us about the second key point in the research project?

The second key point is arithmetic operations using optical interference. Optical interference enables operations to be executed at the speed of light. We proposed an optical parallel adder as an application of binary-decision-diagram (BDD)-based digital arithmetic. This arithmetic unit executes digital addition through a single photoelectric conversion and optical propagation and is expected to achieve a latency about one order of magnitude lower than that of CMOS adders. In cooperation with a research group of AIST, we fabricated a prototype of a 4-bit optical adder and successfully demonstrated full additive operations. Regarding the BDD-based digital arithmetic, we found that circuit size increases exponentially by using multipliers, etc. and searched for a means to avoid this problem. We discovered that circuit size can be reduced using the above-mentioned optical transistors at key points.

Optical interference is an analog operation, so light is most advantageous in analog operations. A typical example of an analog operation that can be executed at the speed of light is a multiply-accumulate operation, which is the most-fundamental operation and a processing bottleneck in deep learning and artificial-intelligence processing using modern NNs. Therefore, we are investigating a photonics-electronics convergence NN architecture using multiply-accumulate operations exploiting optical interference.

We plan to execute a multiply-accumulate operation with an optical circuit using optical interference and execute nonlinear processing called activation, which is necessary at key points in NN processing, with an optical transistor. We then envision a scenario in which we integrate this high-speed analog computing circuitry using light with a CMOS processor by using highly efficient photoelectric conversion technology. In this scenario, the conversion of electrical digital signals to optical analog signals is important. We discovered that digital-to-analog conversion with ultralow latency is possible with the above-mentioned linear-interference logic gate technology and successfully demonstrated circuit operation in collaboration with AIST.

To develop component technologies in accordance with the above-mentioned scenario, NTT and AIST



(a) Topological photonic crystal loaded with phase-change material

(b) Non-Hermitian photonic crystal loaded with graphene

Fig. 2. Structural diagram of a photonic crystal.

developed a prototype optical circuit using advanced silicon-photonics integration technology and are verifying the principle on which the prototype is based. At the same time, a research group at Kyushu University, which has expertise in computer architecture, has been studying an architecture for a photonics-electronics convergence computing system having scalability for large-scale operations achieved by integrating the above-mentioned multiply-accumulate operation unit with CMOS arithmetic circuits.

This research project aims to develop a photonics-electronics convergence accelerator that can operate cooperatively with CMOS by making the most of the characteristics of light-speed operation. We expect that this development will be an important step toward implementing an ultralow-latency and low-energy-consumption information-processing system that is required in the post-Moore era.

—I heard that you have achieved new results concerning topological photonics, which you talked about in the previous interview.

As I reported in the previous interview, we are also conducting basic research to discover new properties of light; in particular, we are working on a new field called topological photonics. This field involves the creation of new physical properties of light by applying the concept of topology to photonic crystals, which we have been researching for many years, and is currently the subject of research activities worldwide. We are particularly focused on developing a dynamically reconfigurable optical-topology system. In topological photonics, new properties are constantly being discovered, and if we can dynamically control these properties, we expect to be able to achieve operations that are currently impossible with conventional optical devices and circuits. We aim to propose two methods for controlling light through optical topological phase transition and dynamic change in optical topology: (i) loading and modifying a nanophotonic structure with functional nanomaterials and (ii) using the peculiar properties of non-Hermitian optical periodic systems using the imaginary part of the refractive index[*1].

Regarding the technology for controlling a nanophotonics structure by adding nanomaterials, we are investigating a method of loading a photonic crystal with a phase-change material, the optical properties of which change significantly with temperature and other factors. By patterning germanium-antimony-telluride (GST)[*2], an excellent phase-change material, and loading it on a photonic crystal, as shown in **Fig. 2(a)**, we found through theoretical analysis that it is possible to induce an optical topological phase transition through a phase change of GST. To demonstrate this theoretical phenomenon, we developed technology for fabricating nanostructures using film deposition and high-precision alignment techniques and succeeded in fabricating silicon topological

*1 Imaginary part of the refractive index: The imaginary part of the refractive index is expressed in complex numbers. A non-Hermitian photonic crystal uses the imaginary part of the refractive index in its optical periodic system.

*2 GST: A compound consisting of germanium (Ge), antimony (Sb), and tellurium (Te) in the formula $Ge_2Sb_2Te_5$.

photonic-crystal structures loaded with submicron-scale GST. We are currently attempting to induce an optical topological phase transition through the crystalline amorphous phase transition of GST.

Thus far, we have developed a laser using an ultra-compact current-injection photonic crystal nanoresonator. Using this laser, we recently fabricated—as a world's first—a coupled system in which two nanolasers are integrated, and used this system to generate a special light state called an exceptional point peculiar to non-Hermitian optics. We also succeeded in observing direct emission of light from this exceptional point. We proposed a method for fabricating a new type of photonic crystal called a non-Hermitian photonic crystal, in which the imaginary part of the refractive index is periodically modulated. As shown in **Fig. 2(b)**, this fabrication process involves patterning graphene[*3] loaded on a photonic crystal with submicron periodicity. We clarified that an exceptional point can be formed on this structure.

We are currently conducting experiments related to generating optical topological-phase transitions and forming topological singularities, which have been initially observed, to obtain quantitative data. For non-Hermitian photonic crystals, we fabricated devices that can control the imaginary part of the refractive index using a technique for selectively loading graphene and researching the control of exceptional points and topological singularities.

Although research on topological photonics and non-Hermitian optics is still in the exploratory basic-research stage, a variety of unknown properties that differ from those of conventional materials have been discovered, and exciting research and development is being conducted worldwide. Singularities with peculiar properties, such as exceptional points and topological singularities, have been reported, and we are conducting our research with the expectation that we will find new means of optical control that will use those properties.

Having light execute computation

—I understand that your research on optical transistors was the impetus for the IOWN concept.

I am glad that our research on photoelectric conversion and optical transistors based on nanophotonics was one of the triggers that hatched the IOWN concept, which aims to introduce light into all areas of communication networks. That said, it was a happy accident. I am quite interested in having light execute computation (in addition to communication), and I believe that light can do a lot more. This idea may sound a bit far-fetched, but in the brain, computations are executed as a result of signals propagating through the NN in the brain. I thought that light, rather than electricity, was more appropriate for those computations. Computing with optical networks can be much faster, so things that were previously unimaginable become possible. In other words, I hope that the pursuit of having light execute computation will lead to the technological elements that will form the foundation of IOWN.

Realizing this idea of having light execute computation through the development of an optical integrated circuit was up for internal discussion during our research on photonic crystals, but we thought it would be a difficult target to achieve. In fact, our collaboration with experts in computer science at JST-CREST led to the actual consideration of the idea. As we began to work with experts in completely different fields, what had previously been a vague idea became a concrete research topic. Through that experience, I realized—even more strongly—that it is important to look at other fields and other worlds.

—What do you think researchers are to society? And what would you like to say to future generations of researchers?

It is our responsibility as researchers to create new knowledge and technologies, and I believe that such a responsibility can be rewarding. If there are no more researchers, current technologies will be unusable or not even exist. In that sense, researchers are necessary for society and to move it forward.

To have my responsibility be rewarding, I try to ensure enough time for my research. Routine tasks come up constantly, but I allocate my time wisely. I think it is important to set aside half a day, or even a full day, for me to concentrate and think freely without being overwhelmed by routine tasks. Having said that, I'm currently in a difficult situation as a researcher because I do not have enough time to spare. If I become aware that I'm in such a situation, I try to find such time, even if I have to push myself.

Finally, to all researchers, remember when you first joined a lab at university and the feeling you had when you were conducting experiments and research for the first time. The research and experiments must have been exciting, right? Today's researchers are

*3 Graphene: A crystal composed of a single atomic layer of carbon.

really busy every day, and I think it is easy to forget what we were like back then, but let's not forget the fun of pursuit and create that fun by ourselves. Exciting research requires preparation. I want you to conduct research in a manner that enables you to continue with that fun.

To students who aspire to become researchers, I feel that Japan today has too few students going on to doctoral programs. In Europe and the United States, a doctoral degree is recognized as a status not only for researchers but also for engineers. Therefore, if you aim to become a researcher or engineer who can play an active role in the world, you should obtain a doctoral degree. When you decide what you want to be/do in the future, don't look at society from a short-sighted perspective but from a long-term perspective.

■ Interviewee profile

Masaya Notomi received a B.E., M.E., and Ph.D. in applied physics from the University of Tokyo in 1986, 1988, and 1997. In 1988, he joined NTT. Since then, his research interest has been to control the optical properties of materials/devices by artificial nanostructures (quantum wires/dots and photonic crystals). He is also a professor at Tokyo Institute of Technology. He received the IEEE Laser and Electro-Optics Society Distinguished Lecturer Award in 2006, JSPS prize in 2009, Japan Academy Medal in 2009, and the Commendation by Japanese Minister of Education, Culture, Sports, Science and Technology in 2010. He served as a member of the National University Corporation Evaluation Committee in the Japanese government. He is an IEEE Fellow and member of the Japanese Society of Applied Physics, American Physical Society, and Optica.

Network Virtualization Technology for an NFV Infrastructure to Drive Innovation in the Network

Yasufumi Ogawa
Distinguished Researcher, NTT Network Innovation Center

Abstract
As network services become increasingly diversified, the difficulty of predicting and dealing with spikes and fluctuations in data communications traffic is becoming apparent. However, studies are now underway at many telecom operators on ways of solving this problem by applying network virtualization technology for a network functions virtualization (NFV) infrastructure (software virtualization) to network services. In this article, we talked with Distinguished Researcher Yasufumi Ogawa about network virtualization technology for an NFV infrastructure.

Keywords: virtualization, NFV infrastructure, open source community

Achieving a low-cost, high-performance network through the virtualization of network software

—Mr. Ogawa, please explain to us the meaning of network virtualization technology for a network functions virtualization (NFV) infrastructure.

Before I talk about network virtualization technology for an NFV infrastructure, I would first like to explain "virtualization infrastructure." Virtualization infrastructure refers to an infrastructure system and technology that can flexibly allocate the computer resources needed to meet a variety of requirements by using virtualization technology. For example, a high-performance machine would be necessary to run artificial intelligence or deep learning programs that have attracted much attention in recent years. For an individual, this would require that the parts and components making up the machine be procured, arranged, and assembled on one's own. However, this process can be simplified by using a virtual machine. In other words, a virtual machine enables an individual to freely use a high-performance machine by tuning and occupying a portion of a huge actual machine in a datacenter for one's own purposes. At this time, a variety of requirements may come into play such as robust security functions and high network performance, but a machine that instantly meets these requirements can be virtually prepared by simple operations such as mouse clicks and menu selection. This is a technical overview of virtualization infrastructure.

Network virtualization technology for an NFV infrastructure focuses more attention on network functions. It can be called, in general, NFV. In this regard, the core functions of a large-scale network

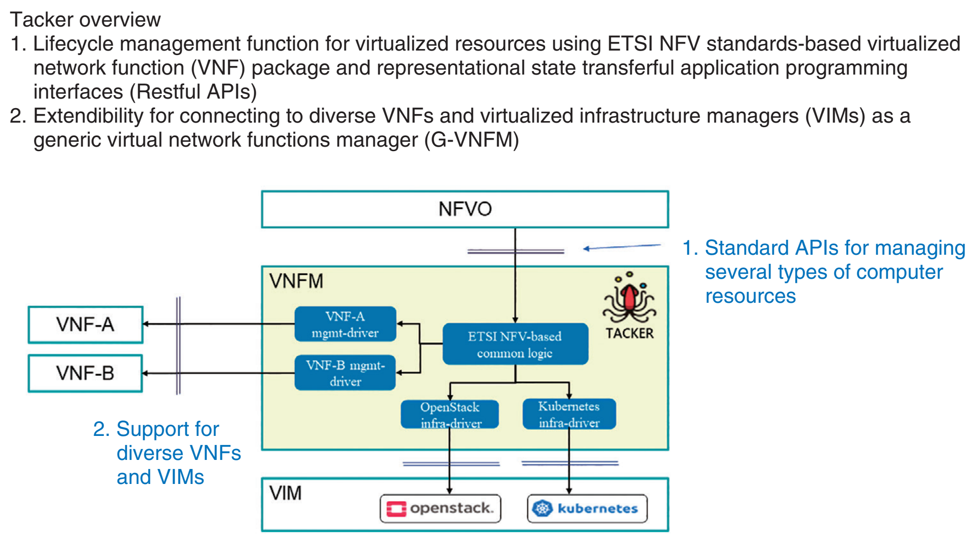


Fig. 1. Overview of OpenStack Tacker.

have extremely strict requirements in terms of quality and performance, but with conventional technology, these could only be met by using expensive dedicated equipment. On the other hand, network virtualization technology for an NFV infrastructure enables such expensive dedicated equipment to be replaced with general-purpose servers and software, which enables, in turn, the construction of a large-scale network in a simple and low-cost manner. Specifically, implementing software that performs the functions of dedicated equipment in existing general-purpose servers makes it possible to construct the equivalent of such dedicated equipment without any physical construction work. This approach offers great advantages for network operators who are concerned with reducing network development costs and shortening development periods.

—What are you doing to achieve network virtualization technology for an NFV infrastructure?

Although elemental technologies such as design techniques for virtual machines themselves and the concepts behind virtual networks have already been established, the current state of affairs is that there are many software development projects in progress. And while implementations are actively moving forward in the open source community and elsewhere, there is still much to be done in meeting requirements such as quality and availability to achieve practical networks. For this reason, NFV standards specified by the European Telecommunications Standards Institute (ETSI), a standardization organization centered in Europe whose members include telecom operators in many countries, are being implemented and provided in software called OpenStack Tacker as an initiative for creating new value (**Fig. 1**).

Tacker is one of the major OpenStack projects that aims to achieve NFV through virtualization infrastructure software. By replacing this with a version fully compliant with ETSI NFV standards, our goal is to be the first in the world to construct a practical and high-quality network infrastructure system. Although the standardization of NFV was already in motion when I began my research, the standards themselves have been evolving to keep up with an industry and requirements that change from year to year. At ETSI, there is a specific update plan for NFV standards, and at present, standards first drafted in Phase 1 have reached Phase 4.

In terms of specific activities, I am currently serving as a Project Team Leader (PTL) in the OpenStack Tacker project, and in addition to providing source code that I write myself, I coordinate decisions on project development policy and take part in Tacker promotional activities. My duties, however, go beyond simply ensuring conformance to ETSI NFV standards targeted by Tacker—I am also involved in providing feedback on problems discovered during development. Furthermore, in addition to making contributions as a developer, I contribute to the expansion of network virtualization technology itself from the standpoint of practical development by interacting with a diverse range of players such as telecom operators and vendors both inside and outside Japan.

—What difficulties come up in the research of network virtualization technology for an NFV infrastructure?

In OpenStack, each project conducts development work independently, and as part of that work, a PTL has discretionary powers such as deciding development policy, formulating rules, and recommending candidates for becoming core members. Moreover, as a project representative, I am also involved in the overall administration of OpenStack. There is a lot of hard work that comes with these activities. For example, I coordinate the extraction of requirements and feedback related to requests for improvements for input to ETSI members, and in the case of a function that NTT would like to include as a requirement, I must make the rounds in obtaining approval from each member. As a specific activity to this end, I promote members that will have a significant say at meetings (core members) from within NTT and among corporate partners with which we closely exchange opinions. I am also involved in providing patches to source code, contributing reviews on improving the quality of patches from developers, sharing knowledge through presentations at international conferences such as OpenInfra Summit, and coordinating activities at OpenStack developer meetings (Project Teams Gathering). It is through efforts like these that I would like to disseminate a variety of technologies in society.

Moreover, at the stage of technology implementation, interconnectivity, etc., any problems that occur must be immediately dealt with. The development of large-scale software like OpenStack makes use of a technique called continuous integration/continuous delivery (CI/CD) as a form of quality management to guarantee the operation of the product itself. Many steps in this technique from source code testing to operation checking are automated. Nevertheless, in actual development, there is a greater than 90% probability that some problems will occur such as design defects in the tests themselves or compatibility issues in libraries due to long-term development. Of course, dealing with these problems may seem like a straightforward issue, but to maintain this sense of normalcy, they must be understood with a broad range of knowledge about software design in existing code. Additionally, when a problem arises, its cause must be analyzed and corrected promptly, so we make a continuous effort to maintain advanced software development skills. Today, as well, new implementations are being incorporated in OpenStack one after another, and keeping up with such a massive code base and guaranteeing its quality is a painstaking effort. On the other hand, I feel that taking on such a challenging task is very rewarding.

Our goal is to provide services that meet the needs of network operators

—What kind of world can be achieved through network virtualization technology for an NFV infrastructure?

As network services continue to diversify, network operators are finding it increasingly difficult to predict and respond to spikes and fluctuations in data communications traffic. As a result, we are entering a situation in which ensuring the reliability of communications as a social infrastructure at the time of a large-scale disaster or other calamity is difficult. There is a particular need to deal quickly with such problems in the mobile network in which the smartphone has become an essential part of daily life. Similarly, in the so-called fixed network that has been supporting telephone services up to now, the conventional way of thinking has been to increase earnings through long-term use of dedicated equipment developed at high cost. At present, however, this model no longer holds due to shortening of the development period and the time to provision as well as shortening of the service lifecycle. Against this background, I believe that we can fundamentally solve a variety of problems and be of great assistance to many network operators by applying network virtualization technology for an NFV infrastructure to these network services to enable speedy and flexible service provision that keeps implementation and maintenance costs down.

In addition, providing a virtualization infrastructure system conforming to ETSI NFV standards has the advantage of ensuring interoperability with a variety of products. Today, large-scale systems are flooded with products having vendor-specific connectivity in which virtualized network function (VNF) testing costs and periods have ballooned and become a problem. Our goal, therefore, is to reduce testing costs on a scale of several billion yen by performing standardized implementation of virtualization infrastructure

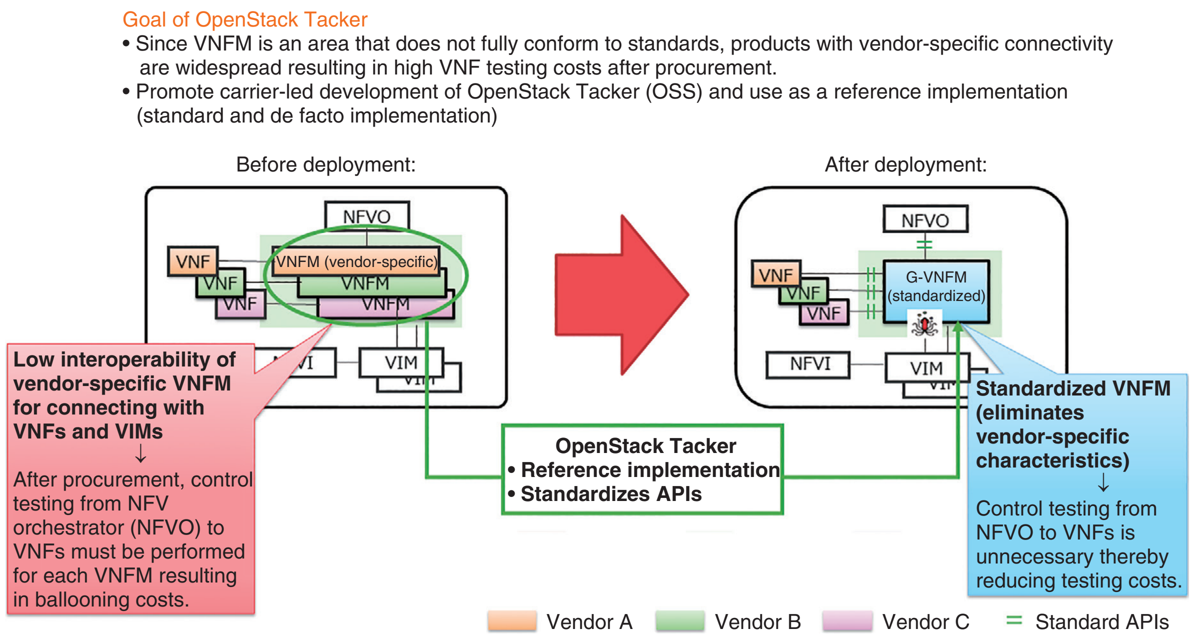


Fig. 2. OpenStack Tacker usage plan and goal.

technology via Tacker to guarantee interoperability and eliminate vendor-specific characteristics (**Fig. 2**). Furthermore, the Innovative Optical and Wireless Network (IOWN) vision proposed by NTT includes an initiative to develop new server infrastructure technology that can both satisfy service requests and reduce power consumption by combining diverse types of devices as a disaggregated computing platform. In terms of software technology in such a lower-layer region, I believe that Tacker can be used to control computing resources on the controlled side and virtual resources installed as software in particular. In this regard, we are endeavoring in our research to achieve a world in which network virtualization technology for an NFV infrastructure can be provided as an infrastructure service incorporating a security and data-centric platform integral to IOWN in lower-layer software.

—What are some important ways of thinking in research and development (R&D)?

As a researcher, I place value on what personally drives me and gives me satisfaction. In software development that I am involved in, a development team has a deadline to meet for each project, and to improve quality while satisfying as many requirements as possible within such an environment, I am sometimes forced as a project leader to pick and choose. At NTT laboratories, I am thoroughly involved in software development and I consider software to be a product of "distress" and "compromise." In short, it is not simply a matter of selecting a path to "compromise." What I want to do is to make the results of our efforts even more useful by placing importance on the "distress" involved in searching for a method that can be achieved in some way. In this way, I believe we can provide services that will please many people and that will provide a sense of accomplishment in R&D not just for me but for all team members as well.

I also place importance on doing work that can be passed on to the next generation. For example, the work that I am doing has the possibility of being passed on to someone else in the future, so in my daily R&D work, I must keep in mind the process of continuously revising and upgrading software design while writing program source code in an orderly and clear manner. By so doing, I am not just creating something that will run well as a function. Rather, I am accumulating many things that anyone can understand just by reading and that can be easily taken over. This is not only for the present—my aim here is to pass the baton on to future R&D.

—Mr. Ogawa, can you leave us with a message for researchers, students, and business partners?

The NTT Network Innovation Center that I belong to is a newly established organization based on the IOWN vision. Its origin can be found in the extensive history of NTT's R&D on telecommunications technologies over many decades, and in my mind, it's an organization that aims to consolidate those achievements toward an even greater goal. I feel that it covers a wide range of research fields from the core network to the access network and that it employs a large number of professionals especially in the practical implementation phase. For example, in network server software, the field that I specialize in, we are involved in the development of various types of applications used by NTT operating companies while having other duties too at standardization bodies and open software communities. I believe that the great strength of R&D at NTT is the many professionals in each field, the use of diverse connections including NTT Group companies, and an environment in which ideas and opinions can be easily exchanged. In addition, NTT has much influence not only within the NTT Group but also with other companies and communities both in Japan and overseas. There are many people that have listened positively to our proposals and become good allies, so for researchers who would like to be globally active, I think that NTT laboratories can be a very attractive place to work.

Our work in the development of network infrastructure technology using open source software (OSS) is very practical in nature within the practical development phase of R&D. Additionally, since we engage in daily discussions on future network technology and become involved with a variety of companies and organizations, we feel that our efforts are extremely worthwhile having a great impact on society. International conferences such as OpenInfra Summit, moreover, give us the opportunity to play an active role at gatherings of prominent researchers from around the world. In addition, standardization organizations and other open source communities can have a great impact on the world since they enable many companies to come together to create standards, specifications, and de facto products in a cooperative manner. To those individuals who would like to take part in such a global community as a software developer or who have an interest in large-scale themes such as creating the network infrastructure of the future, I sincerely hope that you will join us in our activities.

■ Interviewee profile

Yasufumi Ogawa graduated from the Graduate School of Engineering, Osaka University in 2003 and joined NTT the same year. He has belonged to NTT Network Innovation Center since 2021 and has been a distinguished researcher at NTT Network Innovation Center since 2022. He is engaged in the research and development of network virtualization technology for an NFV infrastructure. He has spoken at many international conferences including OpenInfra Summit 2020 and DPDK Summit 2019. He serves as a project leader in the OpenStack community.

Overview and Prospects for Research on Plasmons in Two-dimensional Semiconductor Systems

Norio Kumada and Kazuhide Kumakura

Abstract

Plasmons, which are collective oscillations of electric charges, have a wide range of applications in sensors and other technologies. Plasmons have also been attracting attention as potential new information carriers due to their ability to be generated by light and propagate within a region that exceeds the diffraction limit of light. This article presents an overview of the research on plasmon control and basic physical properties exploiting plasmons at NTT Basic Research Laboratories. Future prospects are also discussed.

Keywords: plasmonics, graphene, semiconductor

1. Plasmons

At elevated temperatures, electrons in a gas can separate from atomic nuclei, resulting in the formation of positive and negative ions and constituting a state of matter referred to as plasma. Examples of natural plasma can be observed in phenomena such as lightning and auroras. Artificial gas plasma can also be generated through the application of high temperatures or high voltages for purposes such as welding, semiconductor processing, and nuclear fusion. Plasma can also exist in solids, derived from free electrons in metals and semiconductors. In solids, because of the high charge density, the Coulomb energy is higher than the thermal energy at ordinary temperatures, causing the behavior of solid plasma to differ significantly from that of gas plasmas. When the electron density distribution in a solid becomes nonequilibrium, an electric field is generated, and the acceleration of electrons in that field tends to restore a uniform distribution of electron density. Thus, an oscillation analogous to the longitudinal waves in a spring occurs in the charge density with overshooting and retraction due to inertia (**Fig. 1**). This plasma oscillation, when treated as a quantum, is referred to as a plasmon.

2. Plasmonics

One characteristic of plasmons is their confinement to regions that are narrower than the diffraction limit[*1] of light at the same frequency. Technology that applies this characteristic in nanoscale regions is referred to as plasmonics (**Fig. 2**). One example of plasmonics is in biosensors, which use the sensitivity of plasmons to the state of the metal surface in nanoparticles. Adhesion of target molecules to the metal surface causes detectable changes in plasmon frequency and attenuation. Other applications include surface-enhanced (or tip-enhanced) Raman spectroscopy, which uses the enhanced plasmon electric field in metal nanoparticles or at the tip of needles, and highly efficient photoelectric conversion. Plasmonics has also been attracting attention in nanophotonics and metamaterials. Nanophotonics deals with the conversion of light to plasmons and the control of plasmon propagation in nanoscale regions. Metamaterials deals with the design of optical properties of materials using plasmonic electric fields in periodic structures that are smaller than the wavelength of light.

*1 Diffraction limit: A limit on optical resolution that is caused by the diffraction of light and is proportional to wavelength.

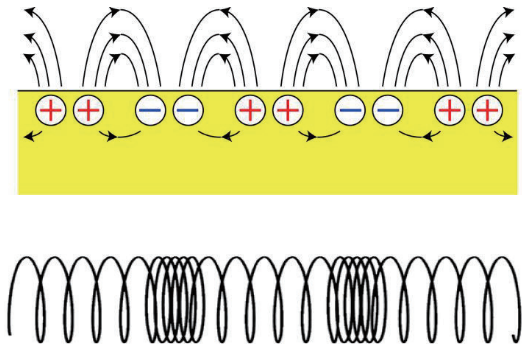


Fig. 1. Longitudinal waves in plasmons (upper) and in a spring (lower).

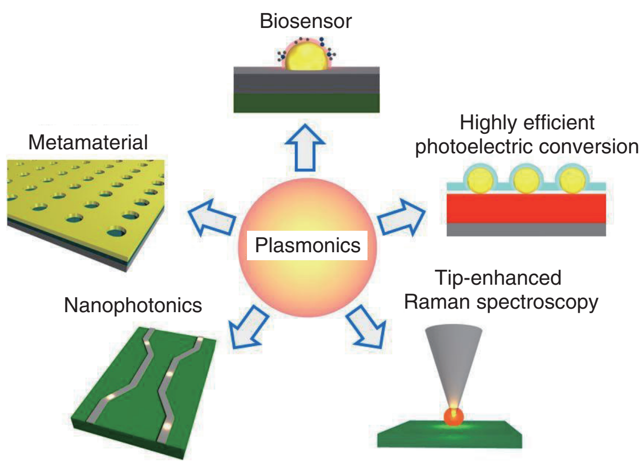


Fig. 2. Example applications of plasmonics.

3. Plasmons in two-dimensional semiconductor systems

Research and application of plasmonics commonly use plasmons that appear on metal surfaces. However, such plasmons have a limited application range due to significant losses and a lack of controllability. In contrast, NTT Basic Research Laboratories focuses on plasmons in two-dimensionally confined electron systems in semiconductor heterostructures and in graphene, a single atomic layer of carbon. The major advantage of two-dimensional (2D) electron systems is the tunability of plasmon characteristics through adjustment of an external electric field. This enables electrical control of plasmon properties. Since the Coulomb interaction in semiconductors is weak compared with metals due to the lower electron density, plasmons in a 2D electron system propagate at a slower velocity with a shorter wavelength, akin to compression waves in springs with a weak spring constant. The tunability and tighter confinement resulting from shorter wavelength make 2D electron systems ideal for applications in which metal surface plasmons are not feasible. Furthermore, application of a magnetic field perpendicular to the 2D plane generates edge magnetoplasmons, which are unique plasmons that propagate in one dimension along the edge of the electron system (**Fig. 3**).

4. Research initiatives by NTT Basic Research Laboratories

Research at NTT Basic Research Laboratories approaches plasmons in 2D electron systems from both applied and fundamental science perspectives. Specifics are explained in the respective Feature

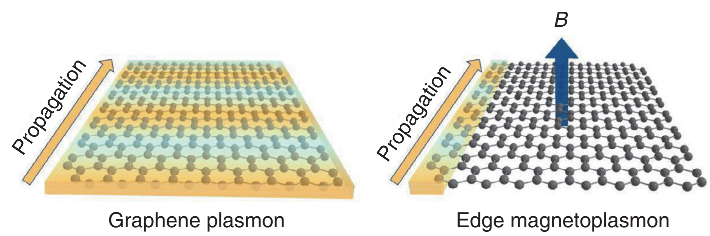


Fig. 3. Illustration of a graphene plasmon and edge magnetoplasmon.

Articles, and a brief overview is given here.

4.1 Active spatial control of terahertz plasmons in graphene

Plasmons in graphene feature low loss in the range from terahertz to near-infrared frequencies and a tunable wavelength with the charge density. The first article presents the results of plasmon excitations at designated frequencies and locations by manipulating the spatial-charge-density profile in graphene using patterned gates [1, 2]. The goal of this research is to construct dynamically controllable plasmonic circuits on graphene.

4.2 Ultrafast optical-to-electrical conversion in graphene

The second article describes the achievement of the world's fastest zero-bias operation of 220 GHz for a graphene photodetector based on the photothermoelectric effect*2 [3, 4]. Photodetectors are key devices in optical communication equipment and sensors, etc. This achievement demonstrates the high potential of graphene as a material for ultrabroadband and ultrafast photodetectors. Application of this achievement would also enable on-chip plasmon excitation and detection. Combining this achievement with the plasmon circuit described in the first article would enable dynamic control of plasmon propagation.

4.3 Theoretical proposal for edge magnetoplasmon crystals

The results of a theoretical analysis of phenomena and functionality in the propagation of edge magnetoplasmons through a network in a periodic 2D artificial crystal structure [5, 6] are presented in the third article. The objectives are to understand the propagation of edge magnetoplasmons with a representation close to that of light and apply the knowledge to improve the manipulation of light.

4.4 Plasmon propagation in a 2D electron-hole system

Measurement of the plasmon-propagation characteristics to determine the state of a system is presented in the fourth article. Time-resolved transport measurement of edge magnetoplasmons is applied to a semiconductor heterostructure that includes 2D electron and hole systems [7, 8]. This technique enables the clarification of the physical properties, such as high-frequency propagation velocity and damping mechanism, in these systems. The objective is future application of the measurement method to topological quantum computation.

5. Prospects for the future

Since graphene was first fabricated by exfoliation from graphite in 2005, it became possible to fabricate materials that do not exist in nature by exfoliating various atomic-layer 2D materials and stacking them. These new materials are expected to reveal new plasmon functions and elucidate physical properties using plasmons. NTT Basic Research Laboratories has been conducting research on plasmons in 2D semiconductors from both basic and applied perspectives. We aim to continuously produce high-impact results through collaboration among researchers involved in these studies.

*2 Photothermoelectric effect: The generation of a voltage when light absorbed by a substance is converted to heat, creating a thermal gradient in the substance. This effect can be used to convert optical signals to electrical signals.

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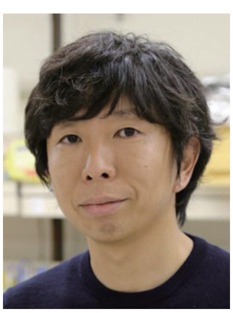

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He received a B.S., M.S., and Ph.D. in physics from Tohoku University, Miyagi, in 1998, 2000, and 2003. He joined NTT Basic Research Laboratories in 2003. Since then, he has been engaged in the study of highly correlated electronic states confined in two dimensions. From 2013 to 2014, he was a visiting scientist at CEA Saclay, France. He received the Young Scientist Award of the Physical Society of Japan in 2008 and the Young Scientists' Prize from the Minister of Education, Culture, Sports, Science and Technology in 2012. He is a member of the Physical Society of Japan.

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Electrical Control of Plasmon Reflectivity in Graphene

Norio Kumada

Abstract

Properties of plasmons in graphene can be controlled electrically. My research colleagues and I have used this feature to verify that plasmons of desired frequencies can be excited in electrically specified regions. This technology can be applied to plasmonic devices such as waveguides and switches.

Keywords: plasmon, graphene, electrical control

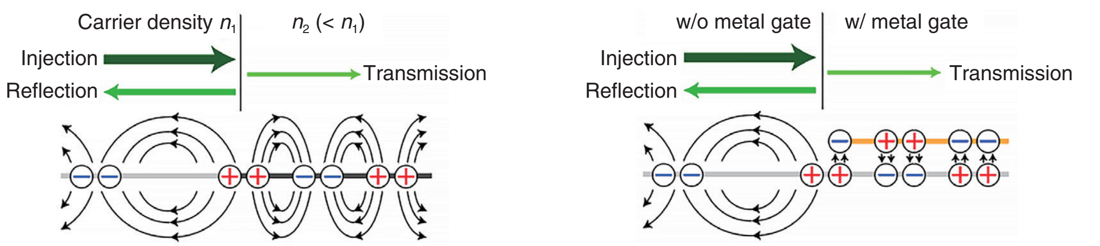
1. Graphene plasmons

Plasmons are collective oscillations of electric charges that have shorter wavelengths than electromagnetic waves at the same frequency and can be confined to regions below the diffraction limit. The technology for manipulating plasmons in nanoscale regions is referred to as plasmonics. Plasmonics has been used in practical devices such as biosensors, as described in the article, "Overview and Prospects for Research on Plasmons in Two-dimensional Semiconductor Systems" in this issue [1]. While surface plasmons excited on metal surfaces are commonly used for plasmonics experiments, they have limitations due to significant losses and poor controllability. These drawbacks have hindered the practical implementation of nanophotonics in which plasmons are used to transmit information in nanoscale structures. Graphene is attracting attention as a plasmonics material that can overcome these problems. Graphene plasmons are known to have low loss in the terahertz and mid-infrared frequency range. Another advantage is that they have a shorter wavelength than metal surface plasmons, which enables them to be confined in smaller regions. Specifically, electromagnetic waves converted into graphene plasmons can be confined to regions 1/1000th the wavelength of the electromagnetic waves. Moreover, the relationship between the wavelength and frequency of graphene plasmons varies with the charge carrier density, providing functions that are not available with metals, such as electrical control of the propagation speed and wavelength of the plasmons by gating. These advantages are expected to pave the way for electrically controllable nanophotonics and new applications, such as electrically tunable metamaterials[*1].

2. Electrical control of graphene plasmons

The relationship between the graphene plasmon wavelength (λ) and frequency (f) varies with the charge carrier density (n): $\lambda \propto \sqrt{n}/f^2$. This indicates that the wavelength decreases as the carrier density decreases at a constant frequency. Therefore, plasmons are reflected at an interface where the charge density changes abruptly, akin to how light is reflected at an interface between media with different refractive indices. Since the carrier density can be varied electrically using a gate electrode, electrically controllable plasmonic devices and circuits can be implemented in principle (**Fig. 1(a)**). While a theory of such active control of graphene plasmons was reported in 2011, it is yet to be verified experimentally because of the technical difficulties in correctly implementing the theoretical concept. For effective control, it is necessary to induce a sharp change in carrier density within a region that is comparably shorter than the plasmon wavelength. However, implementing this using conventional metal gate

*1 Metamaterial: An artificial material the optical properties of which are designed by plasmon electric fields in periodic structures that are smaller than the wavelength of light.



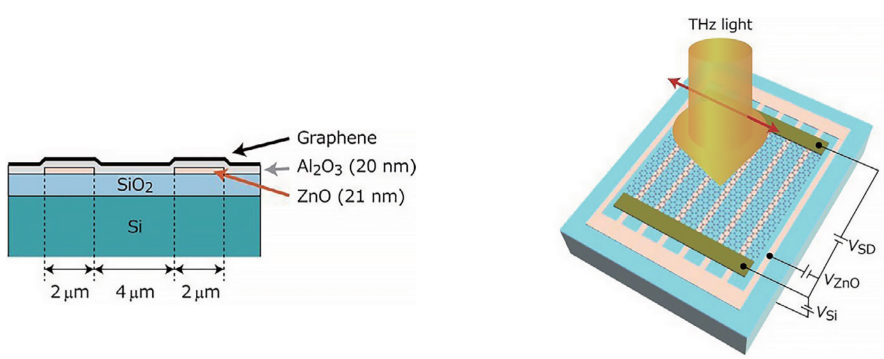
(a) Plasmon reflection at carrier density boundary

Reflectivity varies with the carrier density difference.

(b) Plasmon reflection due to the presence/absence of the metal gate

Uncontrollable plasmon reflection occurs at the boundary regardless of the carrier density profile.

Fig. 1. Graphene plasmon reflection.



(a) Sample structure

(b) Plasmon measurement by terahertz spectroscopy

SiO_2: silicon dioxide
Al_2O_3: aluminium oxide

Fig. 2. Sample structure and measurement method.

structures is challenging as the plasmon electric field distribution results in a substantial change at the boundary between regions with and without the gate resulting from the screening effect*2. This effect causes plasmon reflection at the boundary (**Fig. 1(b)**), which is determined solely by the presence or absence of the metal gate and not by the carrier density profile of the graphene, thus rendering plasmon reflection uncontrollable.

3. Demonstration of graphene plasmon control

The results presented in this article indicate that the confinement and reflection of graphene plasmons can be controlled electrically by using a high-resistivity zinc oxide (ZnO) thin film instead of metal as the gate material, thus avoiding the uncontrollable reflection caused by the metal gate [2]. The screening effect that is inherent in metal gates can be suppressed when the resistance of the gate electrode is high enough that the charges in the electrode cannot follow the oscillatory electric field at plasmon frequencies. To attain this condition, my colleagues and I used 20-nm-thick ZnO with high resistivity that was attained by adjusting the growth temperature as the gate material. The sample used in the experiments had a two-layer gate consisting of a ZnO thin film processed into strips of 2-µm width and 4-µm spacing on a low-doped silicon (Si) substrate (**Fig. 2(a)**), enabling independent control

*2 Screening effect: A phenomenon in which free electrons in a metal move when an external electric field is applied, canceling out the electric field inside the metal.

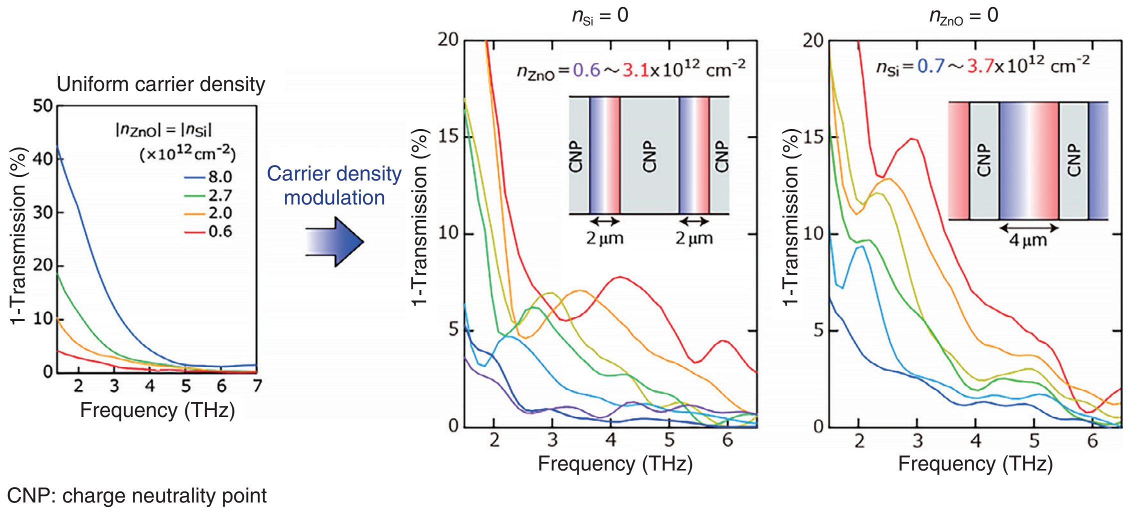


Fig. 3. Spectrum changes due to charge density modulation.

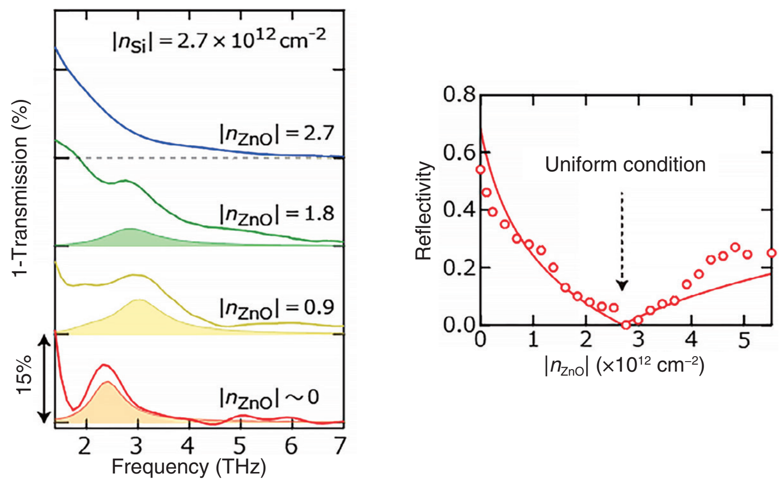
of the carrier density of graphene on the ZnO gate and Si gate (n_{ZnO} and n_{Si}). The plasmonic response in this sample was examined by irradiating terahertz light with an electric field perpendicular to the strips and measuring the transmission spectrum (**Fig. 2(b)**).

Figure 3 shows the extinction spectra of this sample in the terahertz range. When the carrier density is uniform, the absorption of terahertz light by graphene increases monotonically with decreasing frequency. This is typical behavior observed in pristine graphene, indicating the absence of uncontrolled plasmonic reflections caused by the ZnO gate. However, a peak appears in the spectrum when the ZnO gate and Si gate are adjusted such that the carrier density in either region is set to zero (at the charge neutrality point). Because plasmons are not excited in the region at the charge neutrality point, the spectrum peak can be attributed to plasmon resonance in a cavity formed in a region where the charge density is nonzero. We also succeeded in changing the resonance frequency by using the gate. This shows that it is possible to excite plasmons at the desired location and frequency by adjusting the gate voltages. This active spatial control of plasmon excitation can be applied to waveguides, switches, and resonators.

Continuously tuning of the plasmon reflectance at the boundary is also possible by varying the difference between n_{ZnO} and n_{Si}. **Figure 4** shows spectra for several n_{ZnO} values at a constant n_{Si}. As the density difference is increased from a uniform condition, the resonance peak increases with increasing reflectivity. The experimentally obtained plasmon reflectivity (red line in Fig. 4(b)) is consistent with Fresnel's law $R = \left|\frac{\sqrt{n_{ZnO}} - \sqrt{n_{Si}}}{\sqrt{n_{ZnO}} + \sqrt{n_{Si}}}\right|$ used for light reflection. This continuous control of plasmon reflectance can be applied to plasmon modulators and splitters.

4. Future prospects

These achievements provide a platform for implementing the theoretical concept for electrically controllable plasmon circuit. For future work, we plan to advance to experiments on directed plasmon propagation with controlled velocity and phase.



(a) Spectra for several n_{ZnO} at a fixed n_{Si} values

(b) Plasmon reflectivity as a function of n_{ZnO} at a fixed n_{Si}

Fig. 4. Plasmon reflection control.

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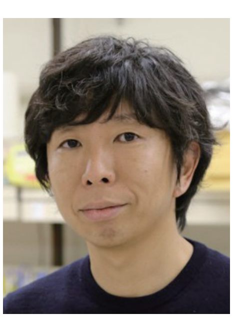

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Ultrafast Optical-to-electrical Conversion Processes in Graphene

Katsumasa Yoshioka, Taro Wakamura, and Norio Kumada

Abstract

Graphene photodetectors have gained significant interest due to their predicted high sensitivity and rapid electrical response to broadband light, offering the potential for superior performance compared with conventional semiconductor devices. However, the experimental evaluation of the operation speed under a zero-bias voltage has been hindered by challenges associated with device architecture and measurement instrumentation, restricting the characterization of graphene's intrinsic dynamics and clarification of its operating mechanism. This article presents an ultrafast graphene photodetector developed at NTT laboratories, detailing the measurement technology and operating mechanism.

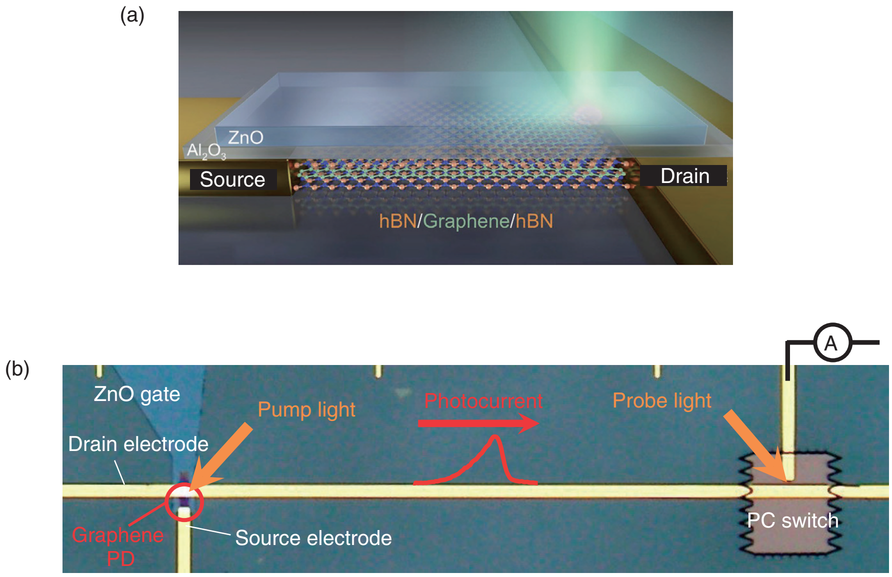
Keywords: graphene, photodetector, terahertz electronics

1. Graphene as an optical-to-electrical conversion device

Photodetectors (PDs) play a crucial role in optical information communications and sensors by converting optical signals into electrical signals. Developing a PD that operates at high speeds for broadband optical signals creates new opportunities for advanced information processing through optical sensors and receivers working across a wide range of frequencies. This requirement can be satisfied with graphene, a promising material that exhibits high efficiency with its ability to absorb 2.3% of incident light with a single atomic layer and operate in an ultrawide frequency band, from terahertz to ultraviolet light [1]. The photothermoelectric (PTE) effect enables graphene PDs to operate at zero bias, which is essential for low power consumption and improved signal-to-noise ratio. However, previous research on graphene PDs has limited the experimental operating speed under zero bias to around 70 GHz [2], far from the theoretical expectation of 200 GHz. The limitations in device structure and measurement systems have hindered the investigation of the intrinsic response of graphene and the clarification of its operating mechanism, leading to a lack of design guidelines for maximizing the performance of graphene PDs. Therefore, the demonstration of 200-GHz operation speed and the elucidation of the physical properties of graphene, including the optical-to-electrical (OE) conversion mechanism, is crucial for further developments in graphene PDs.

2. Ultrafast photocurrent detection based on a novel device architecture and measurement approach

Ultrafast OE conversion in a graphene PD requires a device design that facilitates prompt tracking of incident light signals and a measurement technique capable of high-speed photocurrent detection. To meet these requirements, we used a zinc oxide thin film as a gate material to eliminate the current delay caused by capacitive coupling (**Fig. 1(a)**) and used on-chip terahertz spectroscopy [3] for photocurrent readout (**Fig. 1(b)**). The OE conversion efficiency of graphene PDs using the PTE effect varies significantly with the charge density. Thus, a gate structure must be integrated into the device. Because the gate electrode must possess high conductivity, gold is commonly used as the gate material; however, this limits the operating speed to below 100 GHz due to



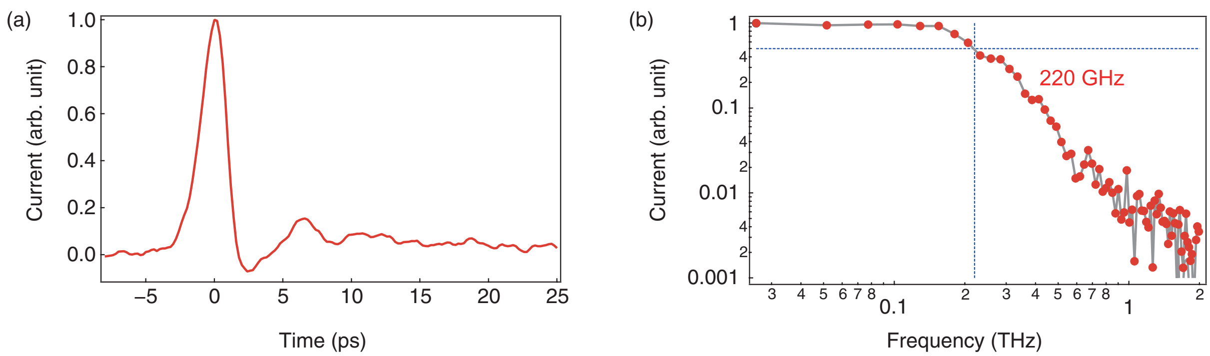
(a) Schematic of a graphene PD. Graphene is sandwiched between hexagonal boron nitride (hBN) as an insulator, and connected to metal source and drain electrodes. After being covered with aluminum oxide (Al_2O_3) insulating film on the surface, zinc oxide (ZnO) is deposited on top as a gate electrode. (b) Microscope photograph of an on-chip terahertz-spectroscopy circuit. When pump light is applied to the graphene PD, the resulting photocurrent is propagated through the drain electrode and detected by illuminating the PC switch with probe light.

Fig. 1. Measurement system for ultrafast OE conversion.

unwanted capacitive coupling. We addressed this issue by using a zinc oxide thin film, which enables control of the high-frequency response by controlling growth conditions. This material possesses a unique combination of being a good conductor for direct-current signals while being transparent at terahertz frequencies [4]. As a result, we successfully eliminated the capacitive coupling-induced current delay. The high-speed oscilloscopes commonly used to read out the photocurrent struggle to measure response faster than 100 GHz because of the bandwidth limitation of the electronics. However, we overcame this challenge by using on-chip terahertz spectroscopy, which enabled us to measure the ultrafast response of the graphene PD with a measurement bandwidth approaching 1 THz through the detection of photocurrent using an on-chip photoconductive (PC) switch. The photocurrent generated by irradiating the graphene PD with a pump pulse (femtosecond laser pulse) propagates through the drain electrode to the PC switch (Fig. 1(b)). Because the PC switch becomes conductive when irradiated by the probe pulse (also femtosecond laser pulse), the signal flows to the ammeter only when the generated photocurrent and probe pulse overlap in time. Therefore, measuring the photocurrent waveform with extremely high time resolution is possible by constantly changing the time difference between the pump and probe pulse. Our innovative device architecture and measurement approach have enabled us to explore the ultrafast OE conversion mechanisms in graphene, which was previously unachievable using conventional methods.

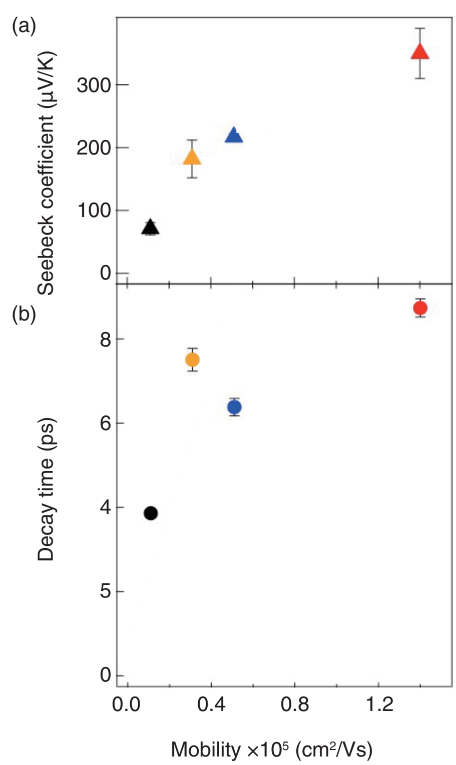
3. Overview of the OE conversion processes in graphene

The photocurrent waveform of the fastest response among measured signals is shown in **Fig. 2(a)**. The various frequency components of the photocurrent obtained by the Fourier transform (**Fig. 2(b)**) show that the 3-dB bandwidth of the graphene PD reaches 220 GHz, more than three times the 70 GHz reported previously and exceeding the theoretical expectation of 200 GHz. This is the first successful extraction of the intrinsic response of graphene unimpeded by device structure or measurement method. To investigate the physical process that determines the dynamical response of the photocurrent, we first focused on the decay time of the photocurrent by fabricating multiple devices with different graphene mobilities.



(a) Time evolution of photocurrent due to optical pulse illumination. (b) The magnitude of each frequency component of the photocurrent obtained by the Fourier transform. The operating speed is 220 GHz, where the current magnitude drops by 3 dB.

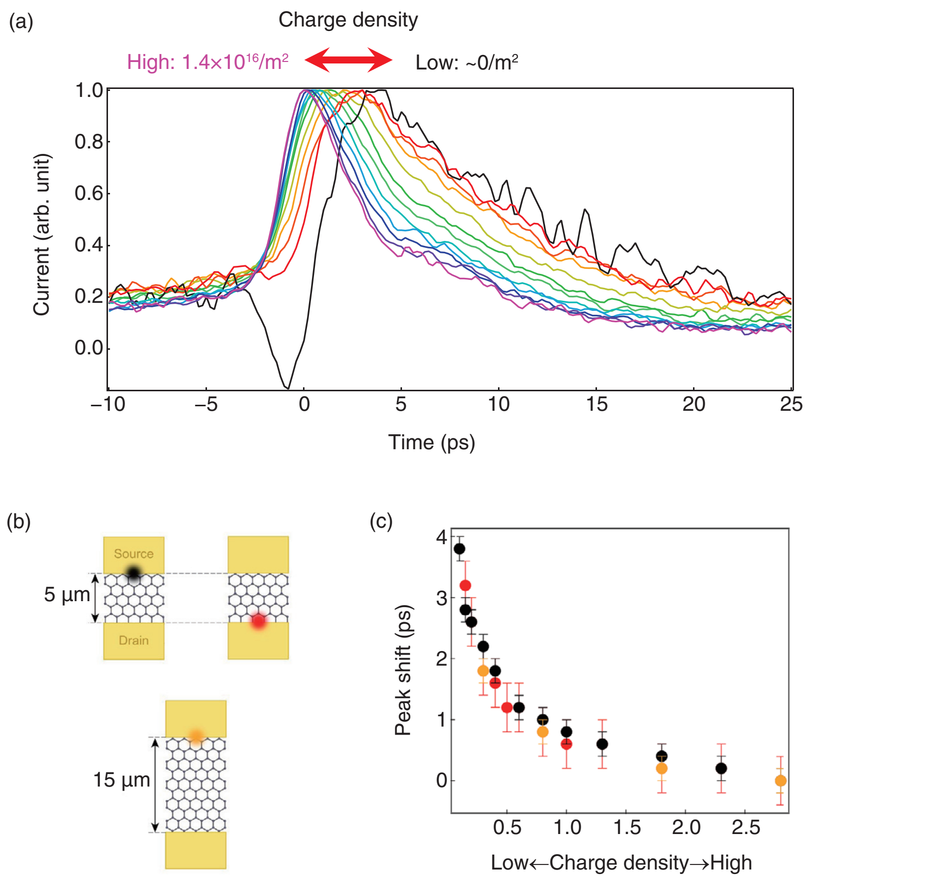
Fig. 2. Verification of operating speed of 220 GHz.



(a) Seebeck coefficient (an indicator of sensitivity). Sensitivity becomes higher when the electron scattering in graphene is small and mobility is high. (b) Decay time (inverse of operating speed). As mobility increases, the scattering decreases and decay time increases (speed decreases).

Fig. 3. Tradeoff between detection sensitivity and operating speed.

Figure 3 shows that lower graphene mobility is associated with shorter decay times. This result suggests that the decay of the photocurrent in graphene is caused by a decrease in the electron temperature in graphene, which is increased by light irradiation. Because of collisions between acoustic phonons and defects, a sample with lower mobility and more defects loses more energy in a single collision event,



(a) As the carrier density in graphene decreases, the time the current peaks after light irradiation becomes 4 ps later. (b) A schematic of the measurement configuration. The current is extracted from the lower drain electrode. (c) The peak shift does not depend on the length or spot position of the graphene.

Fig. 4. Dependence of photocurrent-response time on charge density.

resulting in faster decay times. However, the Seebeck coefficient, which corresponds to PD sensitivity, increases as mobility increases (Fig. 3), so there is a tradeoff between bandwidth and sensitivity in graphene PDs. Therefore, it is necessary to select optimal graphene mobility in accordance with the intended application.

To identify the mechanism that determines the photocurrent generation and propagation response (**Fig. 4(a)**), we investigated the dependence of the photocurrent on the charge density. The results indicate that a decrease in charge density produced a delay in the peak position of about 4 ps. Such a significant peak shift is unprecedented and provides important clues for understanding the OE conversion processes. We can consider two possible causes: 1) the propagation time of the photocurrent through graphene changes or 2) the time for photocurrent generation after light irradiation changes. To test the first possibility, we measured the peak shift for various device lengths and the irradiation position of the pump light (**Fig. 4(b)**). All the results fall on a single curve (**Fig. 4(c)**), indicating that the photocurrent propagation time in graphene is too short to be measured, so the cause of the peak shift must come from the change in the photocurrent-generation time. The ultrashort propagation time in a graphene PD results from its gapless nature. The absence of a bandgap in graphene allows the electric field created by light irradiation to propagate at the speed of light, instantly displacing the electrons near the electrode and generating an immediate flow of current without the need for propagation. The time variation in photocurrent generation is due to the PTE effect, which transforms the electron temperature into a voltage. This means that the non-equilibrium electron state created by the light irradiation quickly settles into a Fermi-Dirac distribution through intraband electron scattering. Our results also indicate that the time it takes for thermal equilibrium is highly dependent on the charge density of the graphene. These findings provide a comprehensive understanding of the ultrafast OE conversion processes in graphene, including the generation, propagation, and decay of photocurrent upon light irradiation [5].

4. Future development

The results presented in this article indicate the high potential of graphene as a material for broadband, high-speed PDs. However, our fabrication process of manually exfoliating graphene from graphite is not suitable for mass production. While the quality of graphene deposited over a large area has been historically inferior to that obtained through exfoliation, the gap is closing as deposition techniques continue to improve. Future studies will focus on evaluating PDs that use large-area graphene to facilitate mass production. Additionally, research in the field of creating novel materials by stacking graphene and other two-dimensional materials could be applied to further enhance the operating speed of PDs. The results of this study could be used to generate, control the propagation of, and detect graphene plasmons in the terahertz range. This opens up the possibility for on-chip handling of plasmon signals, bringing us closer to the goal of creating plasmonic circuits.

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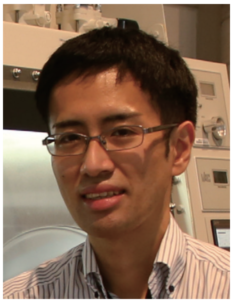

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Theoretical Proposal for Edge Magnetoplasmon Crystal

Ken-ichi Sasaki

Abstract

When a static magnetic field is applied to a two-dimensional electron system, plasmons appear at the edge of the specimen and exhibit peculiar behavior, such as the wave propagation to a single direction along the edge. The calculated results of investigating plasmon propagation when a sample is divided into regions and a crystalline network is formed indicate that the characteristics of the integer/fractional quantum Hall effect, which has been developed in various fields, can be reproduced as optical properties.

Keywords: plasmon, crystalline network, edge state

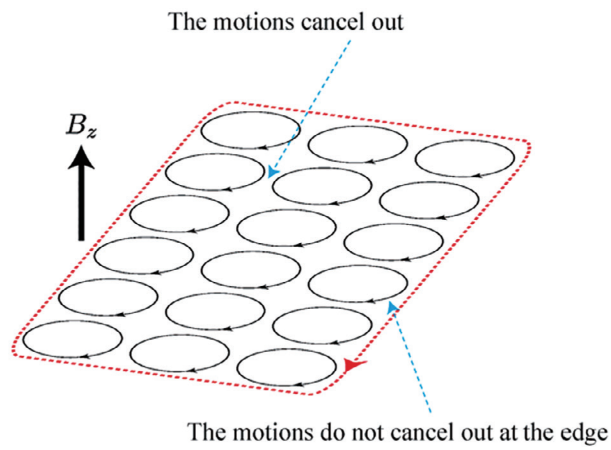
1. Directed wave propagation

Propagating of light to a single direction is not straightforward because when there is a scatterer, light is reflected backwards, reversing the direction of propagation. To take advantage of straightness of light, we use the total reflection by materials such as in optical fibers. It is necessary to use the interaction between light and materials to improve the control of light. For the electrons in materials that emit light, however, such directed propagation can be achieved by applying a strong magnetic field perpendicular to a two-dimensional electron system.*1 The individual electrons in the system take on a circular trajectory, orbiting in a direction that is determined by the magnetic-field vector (cyclotron motion, **Fig. 1**). As is easily visualized on the microscopic level, adjacent electrons move in opposite directions, thus cancel out on the macroscopic level, leaving substantial current produced by many electrons only at the edges of the specimen. This situation is referred to as an edge state and forms a propagation channel along the edge. The propagation direction in the edge state is either clockwise or counterclockwise, depending on the vector direction of the applied magnetic field. What happens when the edge state is excited has been studied since the 1980s. An excited state is a hybrid of electrons and electromagnetic field, and it propagates in a single direction along the specimen edge. It is called an edge magnetoplasmon, because it is a plasmon created at the edge by an external magnetic field.

2. Charge fractionalization

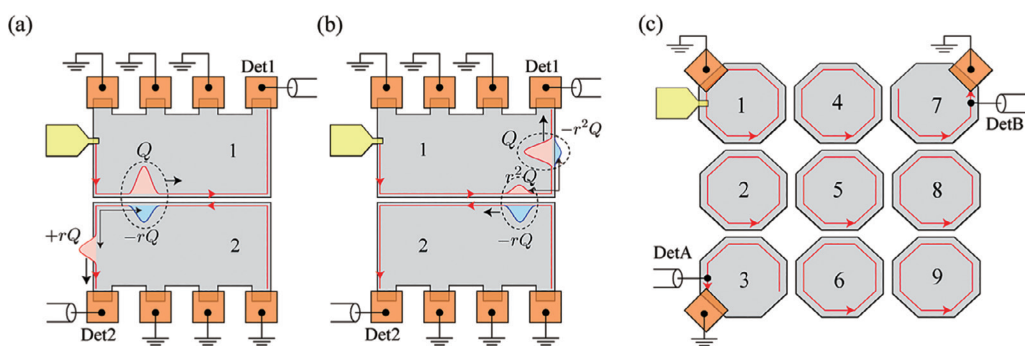
An interesting question is what would happen if a single system in which edge magnetoplasmons circulate is divided into two regions by microfabrication. We divide a specimen into two parts as shown in **Fig. 2**, where the upper part is region 1 and the lower part is region 2. We assume that edge magnetoplasmons exist on the edges of regions 1 and 2 and that the plasmons propagate counterclockwise. In the groove between the two specimens, there are counter-propagating channels (like parallel roads or train tracks) that interact if they are close enough to each other through the electromagnetic interaction (Coulomb potential). Suppose we excited the magnetoplasmon in region 1. Upon reaching the coupled region, a gradation in the charge density (positive and negative charge pair) is formed in region 2, where there had been nothing (Fig. 2(a)). Denoting the charge of the edge magnetoplasmon excited in region 1 as Q, the charge generated at the entry of the

*1 Two-dimensional electron system: A structure in which electrons exist within a two-dimensional plane; a typical example is graphene, which is a planar sheet of carbon atoms that is only one carbon atom thick.



Electron motion becomes circular (cyclotron orbit) under application of a magnetic field that is perpendicular to the plane. Because the electrons are moving in opposite directions relative to adjacent electrons, the motions cancel out at the local level and there is zero net electron motion in the interior. At the edges of the specimen, however, edge states appear and a clockwise current flows around the edges of the specimen.

Fig. 1. Conceptual diagram of a two-dimensional electron system.



(a) Propagation of an edge magnetoplasmon observed near the entrance to the region of opposing edges of the two regions of a two-dimensional electron system divided by microfabrication. (b) Charge fragmentation near the exit of the region of opposing edges. (c) Example of an edge magnetoplasmon crystal.

Fig. 2. Charge-fragmentation phenomenon.

coupled region in region 2 can be denoted as $\pm rQ$, where r is referred to as the coupling constant and represents the strength of interaction between regions 1 and 2 as a value from 0 to 1. An edge magnetoplasmon with a charge of rQ then moves counterclockwise along the edge of region 2, without entering the coupled region, and detected by detector 2. However, a plasmon with a charge of $-r$Q propagates through the coupled region in specimen 2 in the direction opposite normal propagation, pulled by the edge magnetoplasmon that is propagating in region 1. The propagation speed is reduced by a factor of $\frac{1-r}{1+r}$ by the interaction. This fact corresponds to the refractive index of the opposing region expressed as $\frac{1+r}{1-r}$.

When the composite pulse reaches the exit of the opposing region, the $-r$Q component in region 2 loses the attraction of the partner in region 1, and its motion reverses to the normal direction. A charge pair $\pm r^2Q$ is then generated in region 1 and a composite pulse is again created and propagates (Fig. 2(b)). Following

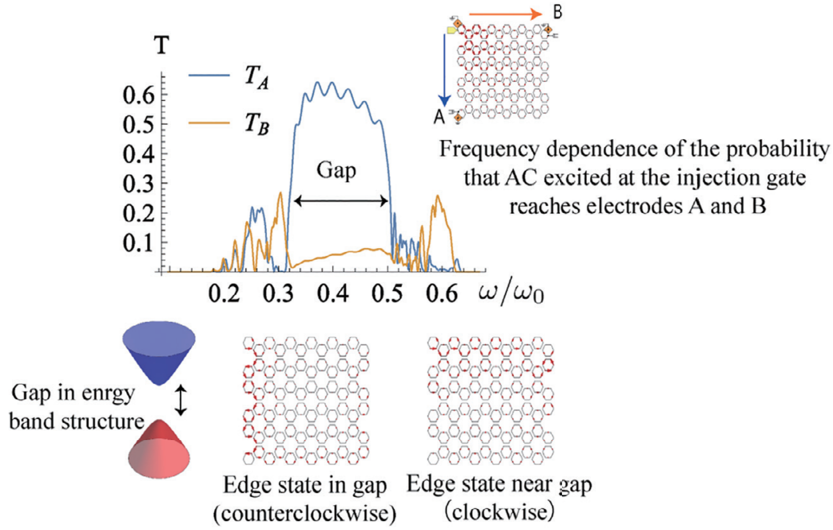


Fig. 3. Propagation in an edge magnetoplasmon crystal.

the time evolution of the pulses in this manner, we see that the charge is progressively fragmented, so the phenomenon is referred to as charge fractionalization. This highly interesting phenomenon was verified experimentally by NTT [1]. Somewhat surprisingly, the familiar reflectance and transmittance for when ordinary thin films are excited by light are calculated on the basis of the AC (alternating current) input given by the angular frequency ω rather than pulses. In other words, the magnetoplasmon is a hybrid state of light and electrons that behaves as light.

3. Edge magnetoplasmon crystal

My current research is an extension of the problem described above, where I considered what phenomena or capabilities appear when a two-dimensional semiconductor is divided into many elements by using microfabrication techniques to produce a semiconductor "crystal" network (for example, a crystal that comprises several "atoms," as shown in Fig. 2(c)). Such problems are a natural direction for extended research. In nanocarbon research, for example, there is a history of increasing the network periodicity of benzene rings from C60 fullerene to planar graphene systems. However, this is not the only motivation. There is also understanding the electronic properties of two-dimensional semiconductors subjected to strong magnetic fields from a perspective that is closer to light and applying that understanding to new areas. For example, assuming the degree of fragmentation to be the diameter of the cyclotron motion, the situation can be regarded as a plasmon optical simulation of a quantum Hall system. One interesting topic is the conditions under which edge magnetoplasmons appear (coupling strength and crystal shape). I believe that the differences between the two types of quantum Hall effects (integer and fractional) can be understood from the viewpoint of edge magnetoplasmons. The integer Hall effect is thought to originate in a single-electron scenario where impurities cause scattering. The fractional Hall effect is believed to result from a many-body effect produced by the interaction between electrons. For edge magnetoplasmon crystals, scattering is caused by defects in the network, and r can serve as a parameter for the electron interaction.

I first calculated the energy band structure of an edge magnetoplasmon to understand the characteristics of propagation through the domain crystal [2]. The details are omitted here, but I used the transfer matrix method for a periodic network without edges. The band structure is a plot of natural frequency versus wavelength and is useful for understanding the state of a crystal. If there is no eigenfrequency for any wavelength within a band, it is referred to as an energy gap within which there is no state for propagation. The calculation results for a honeycomb network of hexagonal "atoms" indicate a band structure that includes energy gaps (**Fig. 3**). The size of the gap between the two cones tends to increase with r

indicating an interaction-induced energy gap. In the original specimen prior to splitting, the edge magnetoplasmons appeared in the energy gap created by quantization*2 of the cyclotron orbits (Fig. 1). That gap was not created by interaction, so gaps in edge magnetoplasmon crystals have a different origin from the original edge magnetoplasmons.

Although I learned that energy gaps also appear in an edge magnetoplasmon crystal, I do not know from the band structure alone (calculation results obtained under the assumption of a periodic edgeless system) whether there are edge modes that propagate along the network edge within those gaps. A more detailed analysis revealed that there are edge modes (Fig. 3). This means that edge magnetoplasmons also exist in edge magnetoplasmon crystals. Interestingly, a mode that moves in the direction opposite normal edge propagation appears at frequencies near the band-gap margins. It is known that edge-state propagation can be bidirectional in the fractional quantum Hall effect. If we consider the interaction between "atoms," the fractional quantum Hall effect caused by the many-body effect can also be taken into account in the calculation. This can be interpreted as the appearance of a mode that propagates in the opposite direction.

4. Conclusion and future prospects

Our understanding of the physical properties of two-dimensional electron systems has undergone broad development, ranging from basic research, such as linking to mathematical topology, to application. The potential of applying this understanding to improving light manipulation is clear. However, the energy scales of electronic states and optical states are generally far apart (the telecommunications wavelength band, for example), and finding a direct link between the two is a difficult problem that requires a new approach. Many researchers are interested in the fusion of the behaviors of light and electrons to produce new capabilities. Inspired by plasmons as a hybrid optoelectronic state, I am searching for such a new approach, and an edge magnetoplasmon crystal is a likely candidate for this purpose. The quantum mechanical behavior of photons at low light intensity has also attracted much interest. The quantum mechanics of edge magnetoplasmons has also been extensively studied, and one topic for future work is the quantum field theory*3 of edge magnetoplasmon crystals.

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*2 Quantization: A process that results in properties having discrete values such as one or two. An example is the number of particles, for which fractional values do not exist. The same concept applies to energy and other such properties.

*3 Quantum field theory: A general term for computational methods that predict the creation, annihilation, and propagation of subatomic particles (photons and electrons, etc.) in time and space.

Time-resolved Measurement of Ambipolar Plasmon Transport in Semiconductor Composite Quantum Wells

Hiroshi Kamata, Hiroshi Irie, Norio Kumada, and Koji Muraki

Abstract

Two-dimensional topological insulators have attracted much attention for potential application to quantum computers on the basis of a new principle. Semiconductor composite quantum wells, in which electrons and holes are confined in separate layers, can serve as two-dimensional topological insulators when their layer structure is optimized. We describe time-resolved measurements of ambipolar plasmon transport in both the electron and hole regimes separately using a single device. This technique will pave the way for investigations of charge and spin dynamics in two-dimensional topological insulators.

Keywords: two-dimensional topological insulators, topological quantum computing, plasmonics

1. Topological quantum computing

Next-generation computers based on new operating principles have been attracting much attention for solving problems such as combinatorial optimization problems, which are difficult to achieve with conventional computers. Quantum computers that execute massively parallel computation by simultaneously encoding multiple units of information on the basis of the principles of quantum mechanics have been extensively investigated. Various proof-of-principle experiments, including fundamental quantum operations such as quantum entanglement, have been demonstrated using single atoms, photons, and electron spins to implement qubits for practical applications. For social implementations of quantum computers, fault-tolerant quantum computation and scalable quantum circuits are recognized as key issues.

Topological quantum computation with quasiparticles,[*1] the unique properties of which differ from those of natural elementary particles,[*2] has been proposed as an alternative approach. Differently from conventional quantum computing, topological quantum computation uses changes in the quantum state of the system triggered by the exchange of quasiparticles as a logic gate. Calculations are executed by sequentially exchanging quasiparticles arranged in space (**Fig. 1**). Since the result is determined only by the order in which the quasiparticles are exchanged and does not depend on the details of the trajectory of the quasiparticles, this qubit is expected to be fault-tolerant against external noise. The two-dimensional topological insulator is expected to serve as a platform on which quasiparticles with unique properties

*1 Quasiparticle: When many particles behave as though they were a single particle, such as the case of electrons in semiconductors, it is referred to as a quasiparticle. In two-dimensional systems, quasiparticles that have the unique properties of exchanging two identical particles exist and follow quantum statistics that differ from those of both fermions and bosons.

*2 Elementary particle: The smallest unit particles that compose natural substances and include fermions such as electrons, and bosons such as photons.

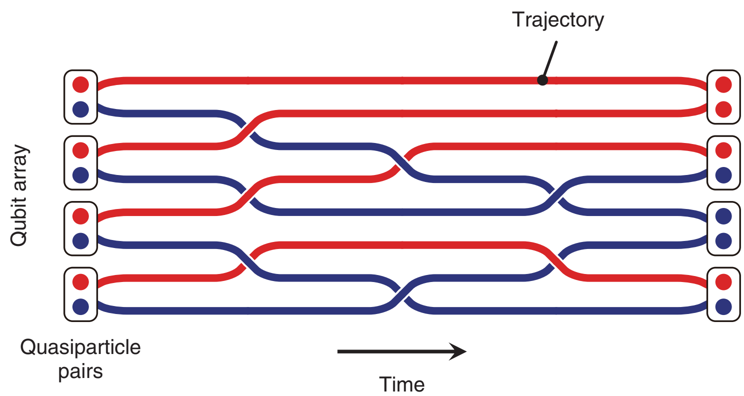


Fig. 1. Schematic image of topological quantum computation.

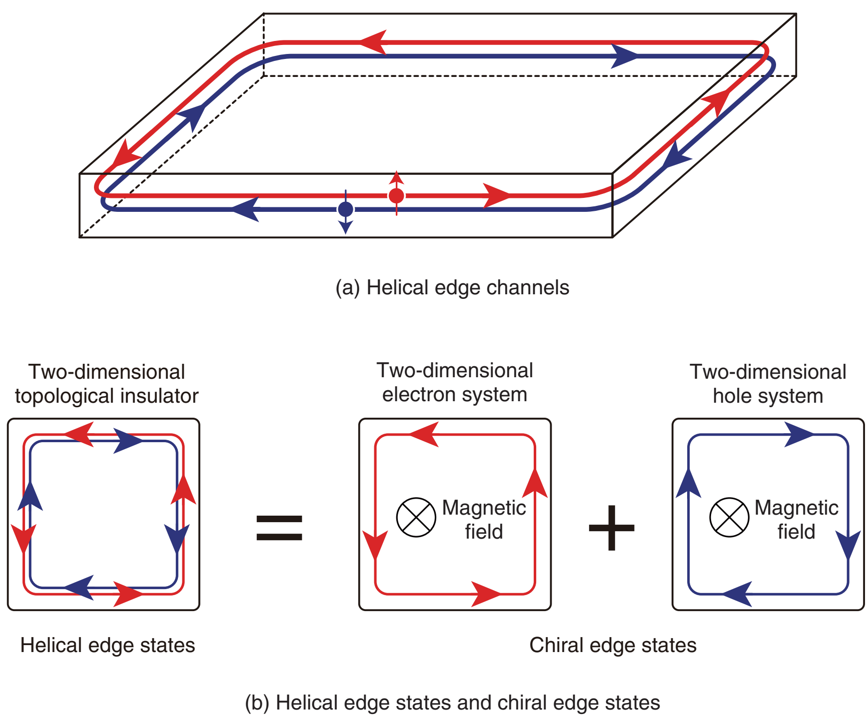


Fig. 2. Two-dimensional topological insulator.

can be generated.

2. Two-dimensional topological insulator

In two-dimensional topological insulators, the interior of the sample is insulating while one-dimensional conductive channels with opposite spins propagating in opposite directions (helical edge channels) are formed along the edge of the sample (**Fig. 2(a)**). Since inelastic scattering between the channels is prevented by time-reversal symmetry,[*3] backscattering is suppressed at zero magnetic field if the sample has no magnetic impurities. The quasiparticles that are key ingredients for a topological quantum computing (Majorana quasiparticles) are expected to

*3 Time-reversal symmetry: The case in which a state does not change, even if the flow of time is reversed; time-reversal symmetry is broken by a magnetic field.

appear in systems where a superconductor is brought to close proximity with the helical edge states. The conductance of the helical edge states should be quantized as theoretically predicted. In experiments, however, quantized conductance*4 has been observed only in samples that have a scale of several micrometers, and the details of the dissipative transport mechanism have not been experimentally understood.

When a strong magnetic field is applied to a two-dimensional electron (hole) system, the cyclotron motion of electrons (holes) is quantized, forming discrete energy levels called Landau levels. In this case, if the Fermi level is placed between the Landau levels, the interior of the sample becomes insulating and one-dimensional conductive channels for which the propagating direction is determined by the magnetic-field direction and charge-carrier type are formed along the edge of the sample (chiral edge channels). This phenomenon is called as a quantum Hall effect, and the system is classified as a two-dimensional topological insulator with broken time-reversal symmetry. Helical edge states in a two-dimensional topological insulator with time-reversal symmetry can be approximately thought of as a superposition of chiral edge states of electrons and holes moving in opposite directions, ignoring the exact spin orientation (**Fig. 2(b)**). At NTT Basic Research Laboratories, we therefore focused on edge transport of plasmons (edge magnetoplasmons) in indium arsenide/indium gallium antimonide (InAs/InGaSb) composite quantum wells, the base material of semiconductor two-dimensional topological insulators. Edge magnetoplasmons are collective oscillations of charges at the edges of two-dimensional systems. By investigating their dissipation and propagation velocity, we can evaluate the characteristics of the edge states.

3. InAs/InGaSb composite quantum well

A composite quantum well consists of InAs and InGaSb sandwiched between aluminum gallium antimonide (AlGaSb) barrier layers. **Figure 3** shows the energy band diagram, where electrons and holes are confined in the InAs and InGaSb quantum wells, respectively. When the bottom of the InAs conduction band is lower than the top of the InGaSb valence band (band-inversion), hybridization of the electron and hole states opens an energy gap, resulting in a two-dimensional topological insulator [1]. When the bottom of the InAs conduction band is higher than the top of the InGaSb valence band (non-band-inversion), the semiconductor has a normal band gap. However, the charge-carrier type can be switched between two-dimensional electron and hole systems by controlling the Fermi level with a voltage applied to the surface gate electrode. We carried out on-chip time-resolved measurements of edge magnetoplasmons in both two-dimensional electron and hole systems using non-band-inverted composite quantum wells.

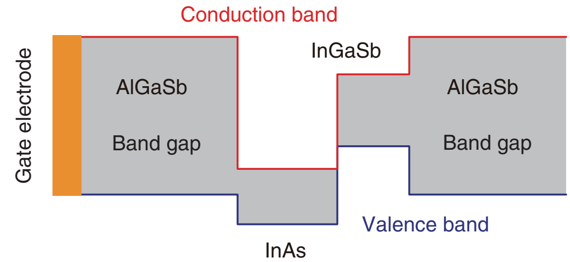


Fig. 3. Energy band diagram.

4. Time-resolved transport-measurement scheme

Conventionally, time- or frequency-domain transport of plasmons in the gigahertz range has been measured with a sampling oscilloscope or spectrum analyzer. However, it has been difficult to observe and evaluate the original plasmon waveform inside a sample because of measurement sensitivity and distortion of high-frequency signals in the measurement system. We succeeded in observing edge magnetoplasmon waveforms inside samples in the time domain by using a method that is similar to pump-and-probe spectroscopy in optical measurement.

Figure 4(a) schematically shows the device structure and experimental setup used in the time-resolved measurements. The structure has an injection gate for exciting edge magnetoplasmons, detection gate for the time-resolved measurement, and global gate for controlling the charge-carrier types and densities. These gates are insulated from each other and from the semiconductor substrate by aluminum oxide (Al_2O_3) insulating layers so that gate voltage can be applied independently to each gate electrode. In addition to an Ohmic contact for measuring current, there

*4 Quantized conductance: Non-dissipative transport in which conductivity is quantized to e^2/h, where e is the elementary charge (1.602×10^{-19} C) and h is Planck's constant (6.626×10^{-34} J • s).

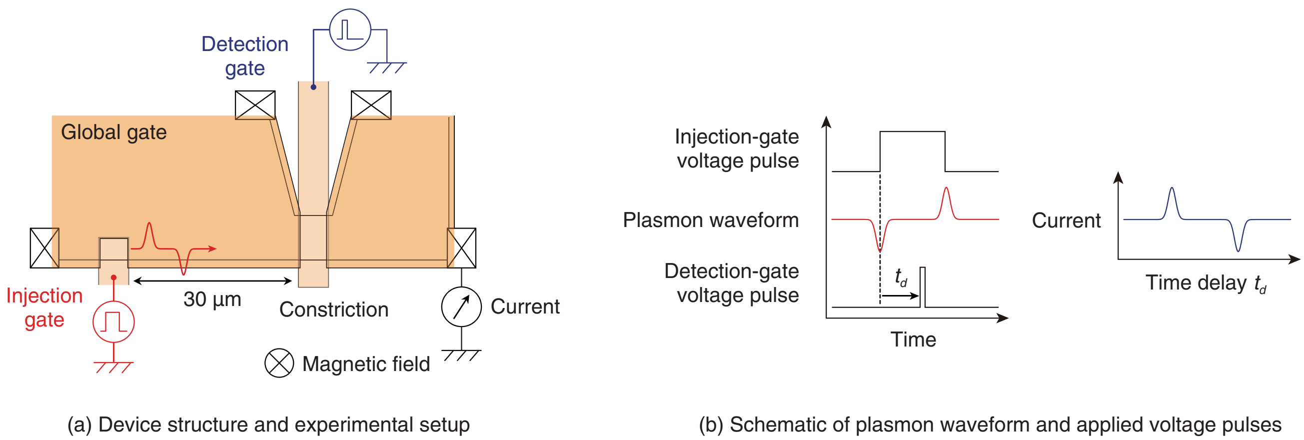


Fig. 4.   Time-resolved measurement scheme.

are several Ohmic contacts for stabilizing the device under the applied high-frequency voltages. The measurements were carried out in the quantum Hall regime under a strong magnetic field at a measurement temperature of 1.5 K.

When a voltage pulse is applied to the injection gate (injection pulse), negative and positive pulsed edge magnetoplasmons are excited at the rising and falling edges of the injection pulse, respectively. The excited edge magnetoplasmons propagate along the edge of the device to the right or left, depending on the chirality determined by the magnetic-field direction and charge-carrier type. For the time-resolved measurement, a short voltage pulse (detection pulse; about 80 ps in width) is applied to the detection gate, which is 30 µm from the injection gate, to temporarily modulate the local carrier density in a constriction (Fig. 4(a)). If the detection pulse coincides with the arrival of edge magnetoplasmons on the constriction, the edge magnetoplasmons are reflected at the constriction; otherwise, the edge magnetoplasmons are transmitted through the constriction and measured at the Ohmic contact located to the right of the constriction. The waveform of the local edge magnetoplasmons propagating in the device can thus be obtained by measuring the current as a function of the time delay t_d on the detection pulse from the injection pulse (**Fig. 4(b)**) [2].

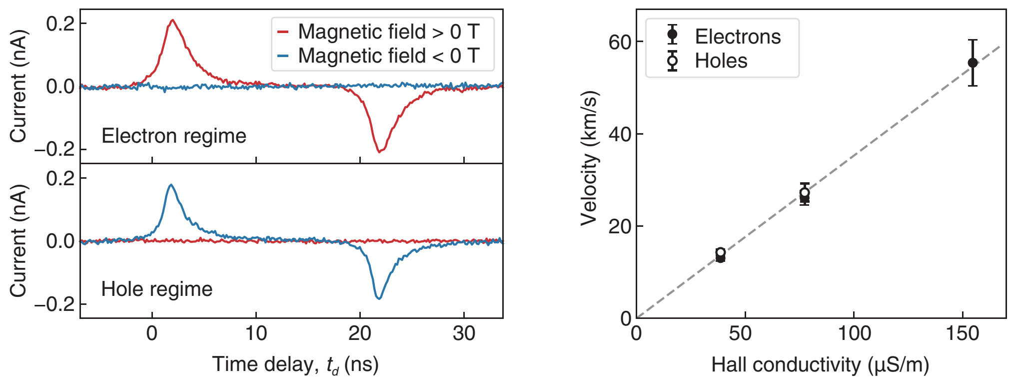
5. Time-resolved measurement of edge magnetoplasmons

An example of edge magnetoplasmon waveforms measured in the electron and hole regimes are shown in **Fig. 5(a)**, where the origin of the time axis represents the time of edge magnetoplasmon excitation. The timing of the positive and negative pulsed waveforms corresponds to edge magnetoplasmons excited at the rising and falling edges of the injection pulse, and the time interval corresponds to the width of the injection pulse. Pulsed waveforms are observed for only one magnetic-field direction depending on the charge-carrier type since electrons and holes have opposite chiralities in the same magnetic-field direction. The peak delay of about 2 ns, which corresponds to the propagation time of the edge magnetoplasmons on the propagation distance (30 µm) yields the propagation velocity.

Theoretically, the propagation velocity of edge magnetoplasmons is proportional to the Hall conductivity when the surface of the device is covered with a metallic gate electrode. The measured propagation velocities for edge magnetoplasmons in the electron and hole regimes are almost identical and proportional to the Hall conductivity (**Fig. 5(b)**). Therefore, the propagation of edge magnetoplasmons in both the electron and hole regimes can be measured in the time domain. This result indicates that the characteristics of the edge channels can be measured as the propagation velocity of the edge magnetoplasmons.

6. Future prospects

At NTT Basic Research Laboratories, we observed edge magnetoplasmon waveforms in the time domain in both electron and hole regimes of an InAs/InGaSb composite quantum well, which is the base material of a two-dimensional topological insulator. Since the



(a) Observed edge magnetoplasmon waveforms

(b) Velocity as a function of the Hall conductivity

Fig. 5. Time-resolved edge magnetoplasmon transport.

measured propagation velocity of edge magnetoplasmons reflects the properties of the edge channels, this time-resolved measurement scheme can be used to investigate charge and spin dynamics and its relaxation mechanism on various materials, including two-dimensional topological insulators. Such experiments will pave the way for developments in topological quantum computing. Furthermore, control of the propagation velocity and chirality of edge magnetoplasmons with gate voltage and magnetic fields are expected to be powerful techniques for plasmonics, in which plasmons are used as information carriers.

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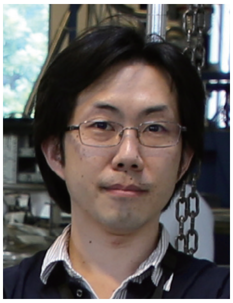

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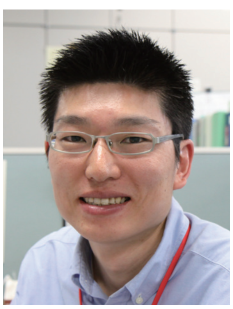

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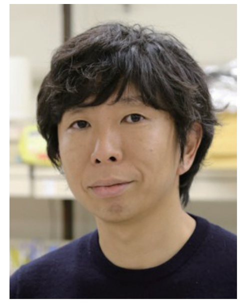

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Ultrafast and Low-power-consumption Membrane Lasers on Si with Integrated Optical Feedback

Nikolaos-Panteleimon Diamantopoulos, Suguru Yamaoka, Takuro Fujii, and Shinji Matsuo

Abstract

We developed energy-efficient membrane III-V distributed-reflector lasers on silicon-based substrates for ultrafast short-reach communication links and neuromorphic computing applications. By leveraging high-speed photon-photon interactions enabled by integrated optical feedback and a high-optical-confinement membrane structure, we demonstrated record-fast directly modulated laser bandwidths and spike-processing rates with ultralow operating energies. This is a step towards our goal of reducing the carbon footprint of information and communication technology and artificial intelligence hardware, while keeping pace with the increasing demand of processing speeds.

Keywords: integrated photonics, membrane lasers, neuromorphic photonics.

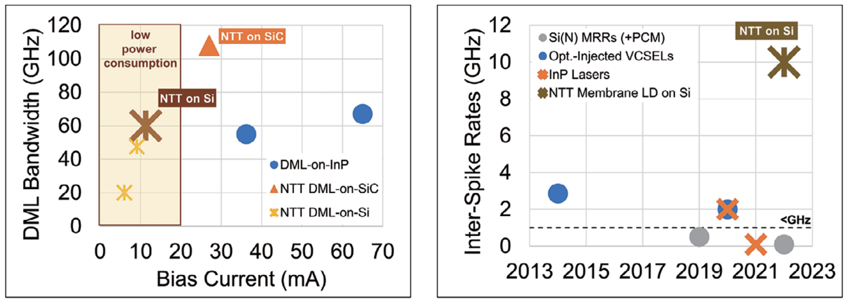
1. Introduction

The advent of modern artificial intelligence and machine learning (AI/ML) applications and cloud services have led to tremendous information and communication technology (ICT) growth, enabling unprecedented processing capabilities. However, as processing and datacenter communication speeds continue to increase, so do their power consumption and associated CO_2 (carbon dioxide) emissions [1, 2]. To support ultrahigh speeds but at reduced power consumption, we developed membrane distributed-reflector lasers with integrated optical feedback for energy-efficient photonics-electronics convergence within NTT's Innovative Optical and Wireless Network (IOWN) project [3, 4].

With our membrane lasers with integrated optical feedback on silicon dioxide/silicon (SiO_2/Si) substrates, we could achieve unprecedented directly modulated laser (DML) bandwidths of ~60 GHz [5, 6] and spike-processing rates (i.e., inter-spike rate) of 10 GHz [7, 8] with sub-pJ/bit and ~pJ/spike laser-operating energies (see **Fig. 1**). We also achieved the world's fastest DML bandwidth of ~108 GHz by integrating our membrane distributed-reflector lasers with integrated optical feedback on silicon carbide (SiC) substrates [9–11].

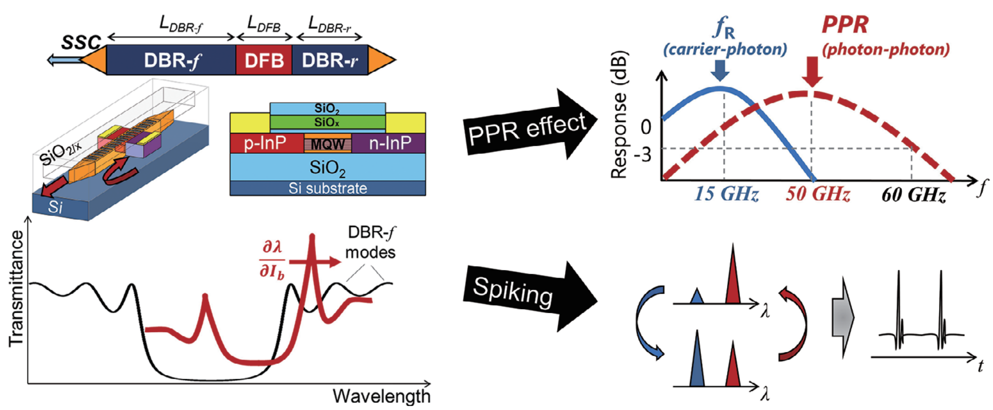
2. Membrane distributed-reflector lasers with integrated optical feedback

Our membrane laser structure for lasers fabricated on SiO_2/Si substrates is based on a distributed-reflector longitudinal design that includes a middle uniform-distributed feedback (DFB) section sandwiched with an 80-µm-long back distributed Bragg reflector (DBR) mirror (DBR-*r*) and 200-µm-long front DBR mirror (DBR-*f*). In this structure, the DBR-*r* is used to filter one of the two DFB modes for single-mode operation [12], and the DBR-*f* is used to generate optical feedback and side-modes for enacting photon-photon dynamics [5, 6, 9–11] (see **Fig. 2**). Very low operating-power consumption was achieved with our heterogenous membrane III-V on Si technology, which uses a thin-film (<350-nm thick) III-V layer on a low-refractive index SiO_2/Si substrate with a similar



InP: indium phosphide
LD: laser diode
MRR: micro-ring resonators
PCM: phase-change materials
Si(N): silicon nitride
VCSEL: vertical cavity surface emitting laser

Fig. 1. Recent records of 3-dB bandwidths of DMLs [5, 6, 9–11] (left) and spike-processing rates of integrated photonic spiking neurons [7, 8] (right).



MQW: multiple quantum well
SSC: spot-size converter

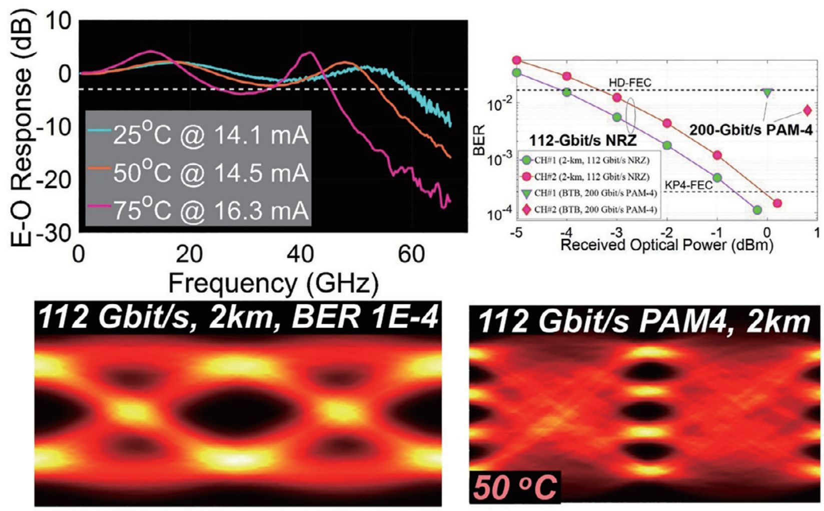
Fig. 2. Membrane distributed-reflector laser with integrated optical feedback [5–11].

low-refractive index SiO_2/silicon oxide (SiO_x) over-cladding. This structure enables very strong transverse optical confinement, which leads to both low operating power and high-speed dynamics. Other advantages include cost reduction by using large Si wafers and mature processes, co-integration capabilities with Si photonics and other integrated photonic platforms, and coupling to fibers via SiO_x-based spot-size converters.

3. Photon-photon resonance for short-reach communication links

Although our previously developed membrane DMLs could achieve high (~20 GHz) bandwidths with sub-pJ/bit energy consumptions [12], there is an inherent trade-off between further DML bandwidth improvement and power consumption since the relaxation oscillation frequency (f_R) is proportional to the square-root of the bias current (I_b) above a threshold (I_{th}), i.e., $f_R \propto (I_b - I_{th})^{1/2}$. This limitation can be alleviated by introducing a photon-photon resonance (PPR) at high frequencies (see Fig. 2) on the basis of the optical-feedback-generated side-modes.

By using the PPR effect, we could effectively triple the bandwidths of the membrane DML-on-Si reaching ~60 GHz [5] while maintaining the same power consumption. This enabled us to achieve 112-Gbit/s short-reach transmissions for datacenter applications [5, 6] (see **Fig. 3**), and the first 400-Gbit/s-class link using a single >100-GHz-bandwidth DML-on-SiC [10]. We also demonstrated the ability to use the PPR



BER: bit error rate
E-O: electro-optical
FEC: forward error correction
HD: hard decision
NRZ: non return to zero
PAM: pulse amplitude modulation

Fig. 3. Transmission performance of membrane DML-on-Si [5, 6].

effect at operating temperatures of 50°C and above, which enabled us to sustain >100-Gbit/s operation for short-reach links using a membrane DML-on-Si at 50°C [5, 6], and more than 100-GBaud modulations under uncooled (85°C) conditions using a membrane DML-on-SiC [11].

4. Spiking membrane laser neurons

One of the most promising neuromorphic computing architectures in terms of energy-efficiency and scalability is the hardware implementation of spiking neural networks (SNNs) due to the unmatched noise-tolerance and event-driven capabilities of spike-information processing. In particular, integrated photonics hold great promise in offering high-bandwidth and scalable on-chip SNNs by taking advantage of the tens-of-GHz speeds offered by modern opto-electronics and the numerous parallelization capabilities of photonics. Nevertheless, most photonic implementations of spiking neurons to date have been limited by physical processes that operate on nanosecond time scales or slower, leading to spike-processing rates (i.e., the factor that ultimately defines the processing speed) of around the GHz level or less.

By using our membrane laser structure with integrated optical feedback, we were able to demonstrate ultrafast spiking behavior with clearly defined thresholds and spiking rates up to 10 GHz using 50-ps-long electrical pulses [7, 8] (see **Fig. 4**), overcoming previous speed limitations. This was achieved by taking advantage of the ultrafast photon-photon dynamics between two longitudinal modes (see Fig. 2). In such a case, a small input energy perturbation can temporarily excite a secondary longitudinal side-mode, which leads to power excitability of ultrashort (~ps long) output optical pulses, when the input energy perturbation exceeds an energy threshold. Moreover, our strong-confinement membrane-III-V-on-SiO_2/Si structure ensured very low operating and threshold energies of ~pJ/spike and ~0.1 pJ/spike, respectively [7, 8].

5. Summary and future plans

To meet the increasing demands on processing speeds of modern ICT and AI applications, while maintaining low operating energies for a sustainable and greener future within the IOWN project, we developed ultrafast and energy-efficient membrane distributed-reflector lasers on Si-based substrates with integrated optical feedback. With such lasers, we could achieve unprecedented DML bandwidths of ~60 GHz and spike-processing rates of 10 GHz with ~sub-pJ/bit and ~pJ/spike, respectively.

Future developments will focus on multi-channel DML transmitters for 800-Gbit/s systems and beyond

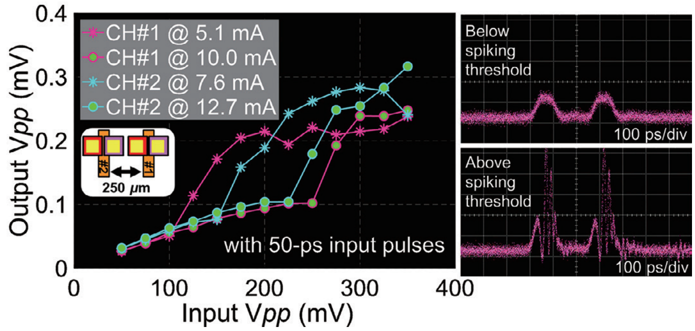


Fig. 4. Spiking effect in membrane lasers on Si [7, 8]. Note: oscilloscope data at ~240-ps inter-spike intervals are shown.

by taking advantage of our previously developed techniques and technologies [13, 14]. We also plan to expand our spiking-membrane laser technology to multi-neuron SNN-PICs (photonic integrated circuits) and showcase their capabilities at solving practical computational tasks at unprecedented processing speeds.

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Report of the First ITU-T TSAG Meeting for the 2022–2024 Study Period

Noriyuki Araki and Jiro Nagao

Abstract

The first Telecommunication Standardization Advisory Group (TSAG) meeting for the 2022–2024 study period of the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) was held from 12 to 16 December 2022 in a hybrid format at ITU Headquarters in Geneva and online. The main outcomes of this TSAG meeting, including the establishment of a Focus Group on Metaverse, are reported in this article.

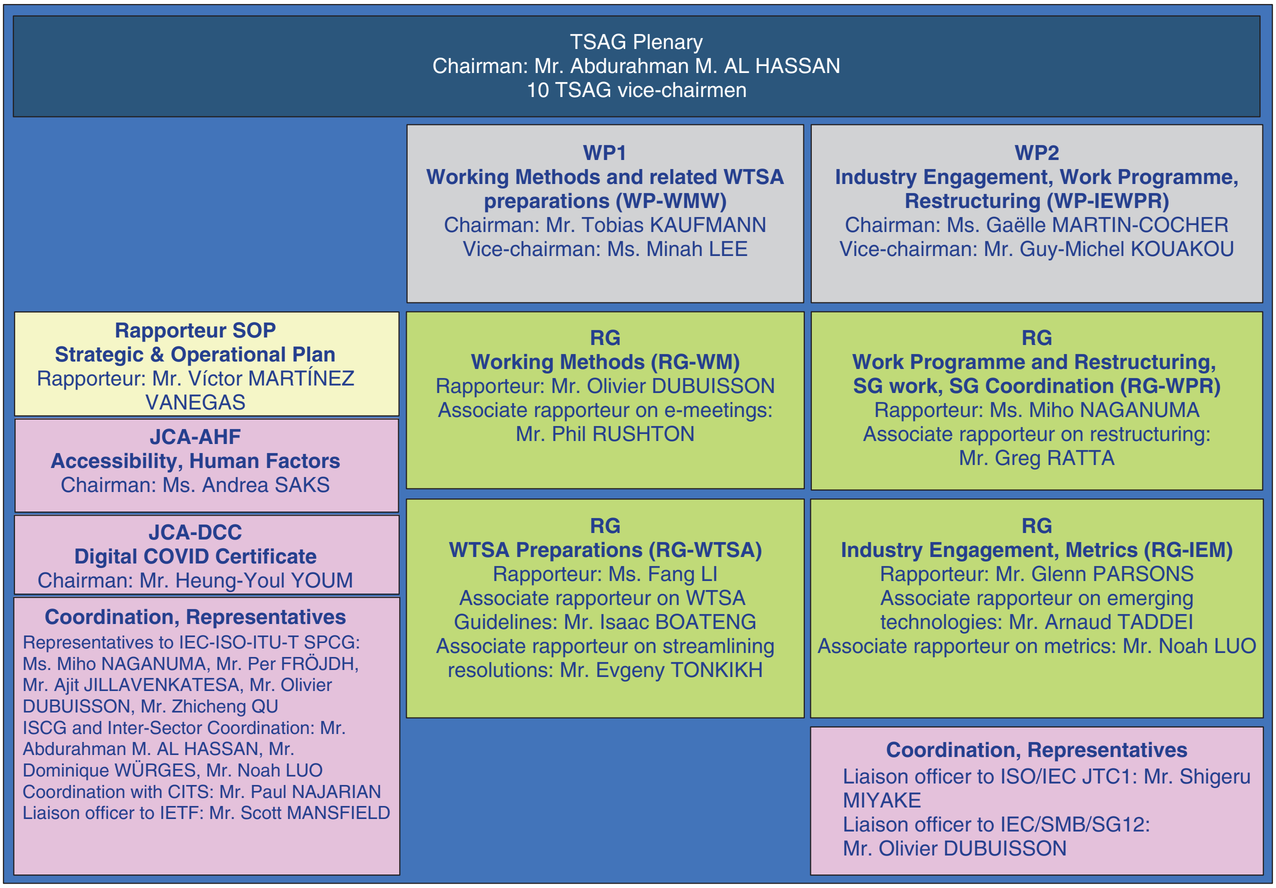
Keywords: ITU-T, TSAG, standardization

1. Introduction

The Telecommunication Standardization Advisory Group (TSAG) reviews the standardization activities of all Study Groups (SGs) of the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) and reviews their working methods, meeting rules, and procedures for cooperation with other standardization bodies. On the basis of an analysis of standardization issues to be addressed by ITU-T in the future, TSAG discusses and proposes an SG structure for the next study period to the World Telecommunication Standardization Assembly (WTSA) [1], which is held every four years.

The first TSAG meeting for the 2022–2024 study period of ITU-T was held from 12 to 16 December 2022 in a hybrid format at the ITU Headquarters in Geneva and online, with approximately 257 participants from 52 countries. From Japan, the ICT Standardization Division, Global Strategy Bureau, Ministry of Internal Affairs and Communications (MIC) headed the Japanese delegation, which consisted of 13 in-person participants including Mr. Seizo Onoe, then director-elect of the Telecommunication Standardization Bureau, and participants from companies and organizations (National Institute of Information and Communications Technology (NICT), the Telecommunication Technology Committee (TTC), NEC, NTT, NTT DOCOMO, OKI, Hitachi), and 8 remote participants from the MIC, KDDI, NICT, Hitachi, Fujitsu, and the ITU Association of Japan.

On the first day of the plenary, the TSAG Management Team proposed a new organizational structure for TSAG meetings, which was approved. The new structure introduces two new Working Parties (WPs), which had not been established before: two Rapporteur Groups (RGs) under WP1, Working Methods (RG-WM) and WTSA Preparations (RG-WTSA), and two RGs under WP2, Working Programme and Restructuring, SG work, SG Coordination (RG-WPR) and Industry Engagement, Metrics (RG-IEM) (**Fig. 1**). Members of the TSAG Management Team are listed in **Table 1**. The TSAG chairman is Mr. Abdurahman M. Al Hassan from Saudi Arabia, Ms. Miho Naganuma from NEC was appointed as one of the 10 TSAG vice-chairmen and rapporteur for RG-WPR, and Mr. Shigeru Miyake of Hitachi was agreed to continue as the liaison officer with the International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) Joint Technical Committee 1 (JTC1).



CITS: Collaboration on ITS Communication Standards
IETF: Internet Engineering Task Force
ISCG: Inter-Sector Coordination Group on issues of mutual interest
SPCG: Standardization Programme Coordination Group

Fig. 1. Structure of TSAG.

2. Establishment of new Focus Groups and Joint Coordination Activities

2.1 Proposal for a new Focus Group on Metaverse

When the Focus Group (FG) on Metaverse (FG-MV) was proposed by ITU-T SG16 (Multimedia), a key point for discussion was which organization should be the parent SG. Establishing an ad hoc group (AHG) for creating Terms of Reference (ToR) was proposed on the first day of the plenary and Ms. Gaelle Martin-Cocher (Canada), vice-chairman of TSAG, was elected as the AHG leader. FG-MV was agreed in the plenary to be newly established under TSAG. Regarding the opinion that the term metaverse should not be used from a trademark point of view, the ITU legal department was consulted, and it was confirmed that there was no problem as it is not about selling a product.

2.2 Establishment of Joint Coordination Activity on Machine Learning (ITU-T JCA-ML)

The request was made by a liaison from SG13 (Next Generation Networks) and was endorsed on the first day of the plenary because of the wide range of issues related to ML among the SGs. The need for collaboration with ISO/IEC and other standards developing organizations (SDOs) dealing with similar ML-related standardization was noted to avoid duplication of efforts.

2.3 Establishment of JCA on Quantum Key Distribution Network (JCA-QKDN)

The FG on Quantum Information Technology for Networks (FG-QIT4N) ended its activities in 2022.

Table 1. TSAG Management Team.

Name	Country	Contact
Abdurahman M. AL HASSAN Chairman	Saudi Arabia	National Cyber Security Authority (NCA)
Khalid AL-HMOUD Vice-chairman	Jordan	Telecommunications Regulatory Commission (TRC)
Ulugbek AZIMOV Vice-chairman	Uzbekistan	Ministry for Development of Information Technologies and Communications
Isaac BOATENG Vice-chairman	Ghana	National Communications Authority
Olivier DUBUISSON Vice-chairman	France	Orange
Tobias KAUFMANN Vice-chairman	Germany	Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway (BNetzA)
Guy-Michel KOUAKOU Vice-chairman	Côte d'Ivoire	ARTCI
Fang LI Vice-chairman	China	CAICT, MIIT
Gaelle MARTIN-COCHER Vice-chairman	Canada	InterDigital Canada Ltd.
Víctor Manuel MARTÍNEZ VANEGAS Vice-chairman	Mexico	Instituto Federal de Telecomunicaciones (IFETEL)
Miho NAGANUMA Vice-chairman	Japan	NEC Corporation
Tobias KAUFMANN WP1 chairman	Germany	Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway (BNetzA)
Minah LEE WP1 vice-chairman	Korea (Rep. of)	Ministry of Science and ICT, TTA
Gaelle MARTIN-COCHER WP2 chairman	Canada	InterDigital Canada Ltd.
Guy-Michel KOUAKOU WP2 vice-chairman	Côte d'Ivoire	ARTCI

The establishment of this JCA was proposed by China and approved because the issues related to QKDN are diverse among the SGs and it is necessary to fulfil a mutual coordination function in a forum such as the JCA.

3. Main results of WP1

3.1 RG-WM

The RG-WM discusses the work methods in ITU-T and the revision of the ITU-T A-series Recommendations (Organization of the work of ITU-T). At this meeting, the activities of the AHG on Governance and Management of E-meetings (AHG-GME), chaired by Mr. Phil Rushton (UK), were reported. This AHG has been the most active group since the last TSAG meeting. He reported that the AHG has met four times since the last TSAG meeting and compiled a list of issues and guidelines for holding e-meetings. After reflecting the revised comments from each country in the editing session, the Supplement 4 to ITU-T A-series Recommendations (A. Suppl. 4) "Supplement on guidelines for remote participation" was agreed upon.

This meeting also agreed on a proposal from Telecom Italia and others to revise A. Suppl. 2 "Guidelines on interoperability experiments and proof-of-concept events" and discussed the Recommendations on working methods and the future course of action for the supplement documents.

3.2 RG-WTSA

The RG-WTSA discusses the consolidation, simplification, and streamlining of Resolutions for WTSA-24. At this meeting, Canada proposed the creation of a one-pager to help WTSA session chairmen work more efficiently by providing a concise summary and reference at hand of the useful guidance found in the A-series Recommendations and Resolution 1. It is envisioned that the one-pager will be developed as an RG-WTSA guideline under RG-WTSA. The proposal was continued for further discussion, as there were different opinions from each country as to whether it is useful or not necessary. There was also a proposal from Russia for the integration and simplification/streamlining of WTSA and Plenipotentiary Conference (PP) Resolutions, and it was agreed to continue the activities for the integration and simplification/streamlining in accordance with the instructions from PP-22, taking into consideration how it should be achieved.

In other discussions, it was agreed to develop guidance on "Principles for Reviewing WTSA Resolutions" and guidelines for the preparation of WTSA resolutions.

4. Main results of WP2

4.1 RG-WPR

The RG-WPR reviews work plans, structures, SG work, and coordination, including the review of activity reports of all SGs, approval of proposed task organization by SGs, coordination of regional groups, coordination among SGs, other SDOs and sectors, and coordination on matters related to SMART (scientific monitoring and reliable telecommunication) submarine cable systems, IMT (International Mobile Telecommunications)-2020, and climate change.

In this meeting, the status reports of each SG were introduced and the activities of other SDOs were reported. The action plan for the SG restructuring analysis was discussed with the U.S. participant as the editor, which aims at a thorough review of potential restructuring options for ITU-T on the basis of the empirical analysis, with a view to approving the SG restructuring proposal at WTSA-24. SG restructuring is an important issue that TSAG needs to address. To move forward with the action plan, the definition of key performance indicators (KPIs)/metrics to be collected and analyzed is to be clarified, the priorities of the various KPIs/metrics to be collected and the timing of their implementation are to be identified, and a project plan for conducting the analysis related to SG restructuring (Gantt chart to WTSA-24) was developed and agreed upon.

4.2 RG-IEM

The RG-IEM discusses measures to promote the participation of industry in ITU-T. At this meeting, Canada proposed to add to the ToR of this RG a requirement to promote participation of next-generation personnel from industry in ITU-T and thoroughly review the current industry involvement process, including the current chief experience officer/chief technical officer (CXO/CTO) meeting-coordination process. There were various opinions such as from a legal perspective, and it is important to consider the obligation to participate as well as acquiring rights through participation, and while some said that attending the CXO/CTO meetings was a very positive experience, other commented that there is an inherent problem of not attracting people from industry to ITU-T. Therefore, it is important to solve this fundamental problem so that the participation of future engineers will increase.

There was also a proposal from China to send a circular including PP resolutions to organizations that are not members of ITU-T to encourage participation of industry. Russia, Saudi Arabia, and others expressed their agreement with the proposal, but there were some who thought that it was a premature idea, and the proposal was finally included as part of the action plan for the future.

5. Future plans

The 2nd TSAG meeting for this study period is scheduled to be held in Geneva from May 30 to June 2, 2023. Due to the short period until the next WTSA, TSAG meetings are scheduled to be held approximately every six months, with the third TSAG meeting scheduled for January 2024. It was proposed that the final two meetings of TSAG for this study period be held in conjunction with the Inter-regional Meetings.

Reference

[1] WTSA-20, https://www.itu.int/en/ITU-T/wtsa20/Pages/default.aspx

Noriyuki Araki

Director, Standardization Office, Research and Development Planning Department, NTT Corporation.

He received a B.E. and M.E. in electrical and electronic engineering from Sophia University, Tokyo, in 1993 and 1995. He joined NTT Access Network Service Systems Laboratories in 1995, where he researched and developed operation and maintenance systems for optical fiber cable networks. He has been contributing to standardization efforts in ITU-T SG6 since 2006. He was the rapporteur of Question 6 of ITU-T SG6 from 2006 to 2008 and rapporteur of Question 17 of ITU-T SG15 from 2008 to 2012. He also served as the chairman of the ITU-T Focus Group on Disaster Relief Systems and Network Resilience and Recovery. He was the vice-chairman of ITU-T SG15 from 2013 to 2022. He also contributes to the activities of International Electrotechnical Commission (IEC) Technical Committee 86 (fiber optic systems). He received the ITU-AJ award from the ITU Association of Japan in 2017. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Jiro Nagao

Senior Manager, Standardization Office, Research and Development Planning Department, NTT Corporation.

He received a Ph.D. in information science from Nagoya University, Aichi, in 2007 and joined NTT the same year. From 2007 to 2011, he was engaged in research and development of image processing and content distribution technology. From 2012 to 2017, he worked for NTT Communications, serving as the technical leader of commercial video streaming services. From 2017 to 2021, he was engaged in research and development of immersive media and presentation technology at NTT Service Evolution Laboratories. Since 2019, he has contributed to the international standardization efforts on immersive live experience (ILE) of ITU-T SG16. He served as an editor of ITU-T H.430.4 (ex H.ILE-MMT) and H.430.5 (ex H.ILE-PE) from 2019 to 2020. He received the ITU Association of Japan Encouragement Award in 2021. He is currently an associate rapporteur of ITU-T SG16 Q8 (Immersive Live Experience, since 2022) and the leader of ILE Sub Working Group of the Telecommunication Technology Committee (since 2020). He is a member of the Institute of Electrical and Electronics Engineers (IEEE), IEICE, and the Japanese Society of Medical Imaging Technology (JAMIT).

50th Anniversary of NTT Yokosuka R&D Center

Tomoyoshi Oono, Kei Karasawa, Takahiro Hamada, Hiroyuki Aihara, Yasushi Okano, Kazuo Hirata, Hirofumi Abe, Minako Izawa, Kyoko Suzawa, Kouichirou Higuchi, and Chika Kitahara

Abstract

NTT Yokosuka R&D Center was established in November 1972 as the third research laboratory of the Nippon Telegraph and Telephone Public Corporation (the predecessor of NTT), and it celebrated its 50th anniversary in 2022. To commemorate this anniversary, the Center held a commemorative event on December 9, 2022. At the event, Mr. Shinjiro Koizumi, a member of the Japanese House of Representatives, and Mr. Katsuaki Kamiji, mayor of Yokosuka City, gave their greetings, and many executives from Yokosuka-based companies and organizations attended the event, which reaffirmed the bond between the Center and the community.

Keywords: regional cooperation, NTT, Yokosuka

1. Introduction

Blessed with good weather, the NTT Yokosuka R&D Center 50th Anniversary Lecture was held on December 9, 2022. The event was attended by approximately 100 guests, mainly companies and organizations based in the Yokosuka Research Park (YRP), the nearby neighborhoods of Yokosuka City, as well as alumni of NTT Yokosuka R&D Center. It provided an opportunity to introduce the past and present achievements of the Center and reaffirm our commitment to deepening regional ties and contributing to social development through regional cooperation (**Photos 1**, **2**).

2. Commemorative speeches

In the first commemorative speech, Tomoyoshi Oono, senior vice president, head of NTT Service Innovation Laboratory Group, introduced Yokosuka R&D Center at the beginning of his lecture and showed a commemorative video (**Photo 3**).

NTT Yokosuka R&D Center was opened in November 1972 by then President Shigeru Yonezawa of the Nippon Telegraph and Telephone Public Corporation with the declaration that it would "conduct research under five themes: information-processing systems for data communications, large-capacity-transmission systems, ocean-communications systems, development and application of satellite communications, and research and practical application of mobile communications."

These themes spread throughout the world in the form of the popularization of the Japanese-made general-purpose mainframe-computer series "DIPS (Dendenkosha Information Processing System)," the construction of optical backbone communications networks, the launch of Japan's first domestically produced communications satellite, and the development of mobile communications that started from car phones and led to smartphones. Another technology that has flourished at Yokosuka R&D Center is image-encoding technology. Image-coding technology began with the research and development of

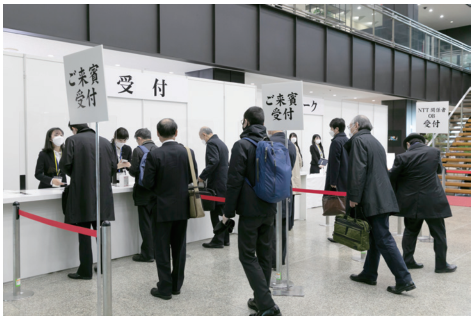


Photo 1. Reception.

Photo 2. 50th anniversary event-management executives.

Photo 3. Mr. Oono, senior vice president, head of NTT Service Innovation Laboratory Group.

Photo 4. IEEE Milestone (G3FAX).

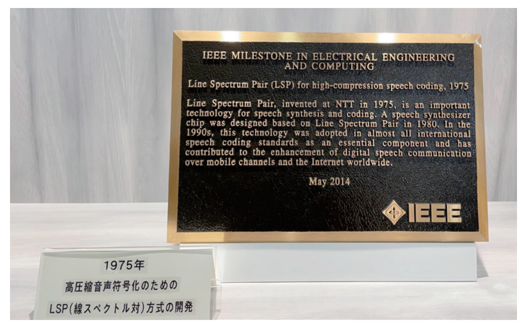


Photo 5. IEEE Milestone (LSP).

facsimile (fax) machines and culminated in the establishment of the G3FAX international standard in 1980, which was awarded an IEEE Milestone in 2012 (**Photo 4**).

In 2014, our high-compression speech-coding technology, called Line Spectrum Pair (LSP) and developed in 1975, was recognized with an IEEE Milestone (**Photo 5**). This award resulted from the adoption of LSP as the voice-coding standard of the U.S. federal government in 1991 as well as its inclusion in the 3rd Generation Partnership Project (3GPP) and 3GPP2 standards for third-generation cell phones in 1999. As of December 2022, 41 Japanese companies have been awarded IEEE Milestones in recognition of technologies and achievements—such as the Tokaido Shinkansen bullet train, automatic ticket gates for train stations, solar cells, VHS (Video Home System) video, and car-navigation systems for automobiles—that have provided the foundation for modernization.

In the 1990s, NTT's image-and-video coding technology was standardized. For example, in 1990, when NTT held the chair of the ITU-T (International Telecommunication Union - Telecommunication Standardization Sector) working group (WG), H.261 was internationally standardized for video coding. Around that time, when NTT was leading international standardization as the chair of the International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) Joint Technical Committee 1/Subcommittee 29, MPEG (Moving

Photo 6. US Emmy Award for Technology Development.

Photo 8. Mr. Koizumi, member of the House of Representatives.

Photo 7. Mr. Kamiji, mayor of Yokosuka City.

Photo 9. Mr. Kinoshita, vice president, head of NTT Human Informatics Laboratories.

Picture Experts Group)-2, which is the basis of digital broadcasting, received the US Emmy Award for Technology Development (**Photo 6**). In 1994, when NTT held the chair of the ISO WG, the JPEG (Joint Photographic Experts Group) still-image-coding system was also standardized.

Next to speak, Mr. Kamiji expressed his expectations for an approach to solving problems through the fusion of cyberspace and physical space taking the post COVID-19 pandemic era into consideration (**Photo 7**). After that speech, focusing on Yokosuka, Mr. Koizumi gave a speech on the concept of developing human resources to deal with cybersecurity, which is an imminent threat in cyberspace (**Photo 8**).

Next, Shingo Kinoshita, vice president, head of NTT Human Informatics Laboratories, who was representing the Yokosuka R&D Center, introduced the results of the united challenge of NTT laboratories targeting the Tokyo 2020 Olympics, namely, the most-recent achievements of the Yokosuka R&D Center (**Photo 9**). Following him, five young researchers talked about their efforts targeting the upcoming Expo 2025 Osaka, Kansai, Japan (**Photos 10–14**).

The presentations by young researchers on their efforts targeting the Expo 2025 were well received by the guests, who were especially impressed to see young researchers working energetically on their research. NTT Senior Executive Vice President Katsuhiko Kawazoe, concluded the speeches by thanking all the guests for their attendance, and the speeches ended on a high note (**Photo 15**).

3. Demonstration exhibitions

Before the start of the speeches and during the social gathering, two demonstrations from each research laboratory—ones selected because they seemed to be easy for the guests to understand—were conducted. The details of each demonstration are listed in **Table 1**. Many of the guests who were unable to attend the NTT R&D Forum took the

Photo 10. Mr. Muraoka, researcher at NTT Human Informatics Laboratories.

Photo 11. Ms. Kozuka, researcher at NTT Computer and Data Science Laboratories.

Photo 12. Mr. Sano, researcher at NTT Social Informatics Laboratories.

Photo 13. Ms. Miura, researcher at NTT Network Innovation Laboratories.

Photo 14. Mr. Nagano, researcher at NTT Access Network Service Systems Laboratories.

Photo 15. Katsuhiko Kawazoe, NTT senior executive vice president.

opportunity to experience in detail the latest research of NTT laboratories (**Photo 16**).

4. Social gathering

At the social gathering, after a toast given by Atsuko Oka, NTT executive vice president, head of R&D Planning, everyone enjoyed talking about the old days with their alumni.

5. Concluding remarks

The previous 40th anniversary was held in a mood of self-restraint, partly because it was right after the

Table 1. Demonstration exhibitions.

	1F Exhibition Hall (dynamic exhibitions)	In front of 10F Lecture Hall (static exhibitions)
Human Informatics Laboratories	Remote World (piano-scale performance)	Metaverse in the IOWN Era
Social Informatics Laboratories	Secure Optical Transport Network Technology	Social Well-being
Computer & Data Science Laboratories	Personalized Sound Zone	MediaGnosis
Network Innovation Laboratories	Ultra-low-latency Video-transmission Technology	Digital Coherent Optical Transmission Technology
Access Network Service Systems Laboratories	Extreme NaaS	Future Wireless Infrastructure Technologies for Realization of 6G/IOWN Concept

IOWN: Innovative Optical and Wireless Network
NaaS: network as a service

Photo 16. Exhibition area.

Photo 18. A scene from the social gathering.

Photo 17. Atsuko Oka, NTT executive vice president, head of R&D Planning.

Great East Japan Earthquake. This time, the COVID-19 epidemic was still spreading, so we paid close attention to infection-control measures, such as asking all attendees to take antigen tests before participating. We are confident that this commemorative event significantly contributed to increasing the presence of NTT Yokosuka R&D Center in the YRP area as well as Yokosuka City through strengthening ties and laying the foundation for future collaborations that will produce significant achievements.

Authors: (from left in the top layer) Tomoyoshi Oono, senior vice president, head of NTT Service Innovation Laboratory Group; Kei Karasawa, general manager of Planning Department, NTT Service Innovation Laboratory Group; Takahiro Hamada, director of Research Promotion, NTT Service Innovation Laboratory Group; Hiroyuki Aihara, general affairs manager, NTT Service Innovation Laboratory Group; (from left in the middle layer) Yasushi Okano, business support manager, NTT Service Innovation Laboratory Group; Kazuo Hirata, research promotion division manager, NTT Service Innovation Laboratory Group; Hirofumi Abe, information strategy section manager, NTT Service Innovation Laboratory Group; Minako Izawa, information strategy section manager, NTT Service Innovation Laboratory Group; (from left in the bottom layer) Kyoko Suzawa, research promotion division manager, NTT Service Innovation Laboratory Group; Kouichirou Higuchi, general affairs department chief, NTT Service Innovation Laboratory Group; Chika Kitahara, General Affairs Department staff, NTT Service Innovation Laboratory Group.

External Awards

Best SEIP Paper Award
Winners: Shinobu Saito, NTT Computer and Data Science Laboratories; Kenji Takahashi, NTT Security; Yasuyuki Hamada, NTT Security; Jan Vermeulen, NTT Americas
Date: December 7, 2022
Organization: 29th Asia-Pacific Software Engineering Conference (APSEC 2022)

For "RP2A: Rare Process-Pattern Analysis - Identifying Potential Problem Process-Patterns by Analyzing System Execution Data."
Published as: S. Saito, K. Takahashi, Y. Hamada, and J. Vermeulen, "RP2A: Rare Process-Pattern Analysis - Identifying Potential Problem Process-Patterns by Analyzing System Execution Data," Proc. of APSEC 2022, pp. 432–436, Virtual, Dec. 2022.

Electronics Society Activity Testimonial
Winner: Koji Azuma, NTT Basic Research Laboratories
Date: March 7, 2023
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE) Electronics Society

For contribution as a co-chair of the 12th Quantum Information Technology Symposium steering committee.

Young Researcher's Award
Winner: Shimpei Shimizu, NTT Network Innovation Laboratories
Date: March 9, 2023
Organization: IEICE

For "Bandwidth Extension of PPLN-based Optical Parametric Amplification."
Published as: S. Shimizu, T. Kobayashi, T. Kazama, T. Umeki, M. Nakamura, K. Embutsu, T. Kashiwazaki, K. Watanabe, and Y. Miyamoto, "Bandwidth Extension of PPLN-based Optical Parametric Amplification," Proc. of the 2022 IEICE Society Conference, B-10-28, Virtual, Sept. 2022.

Awaya Prize Young Researcher Award
Winner: Tatsuya Kako, NTT Computer and Data Science Laboratories
Date: March 16, 2023
Organization: Acoustical Society of Japan

For "Simulation of Open-back Enclosure for Open Ear Hearable Device."
Published as: T. Kako, H. Chiba, and K. Kobayashi, "Simulation of Open-back Enclosure for Open Ear Hearable Device," Proc. of 2022 Autumn Meeting of the Acoustical Society of Japan, pp. 417–418, Hokkaido, Japan, Sept. 2022.

Best Paper Award
Winners: Kei Fujimoto, NTT Network Innovation Center; Ko Natori, NTT Network Innovation Center; Masashi Kaneko, NTT Network Innovation Center; Akinori Shiraga, NTT Network Innovation Center
Date: April 10, 2023
Organization: IEICE

For "Energy-efficient KBP: Kernel Enhancements for Low-latency and Energy-efficient Networking."
Published as: K. Fujimoto, K. Natori, M. Kaneko, and A. Shiraga, "Energy-efficient KBP: Kernel Enhancements for Low-latency and Energy-efficient Networking," IEICE Trans. Commun., Vol. E105-B, No. 9, pp. 1039–1052, Sept. 2022.