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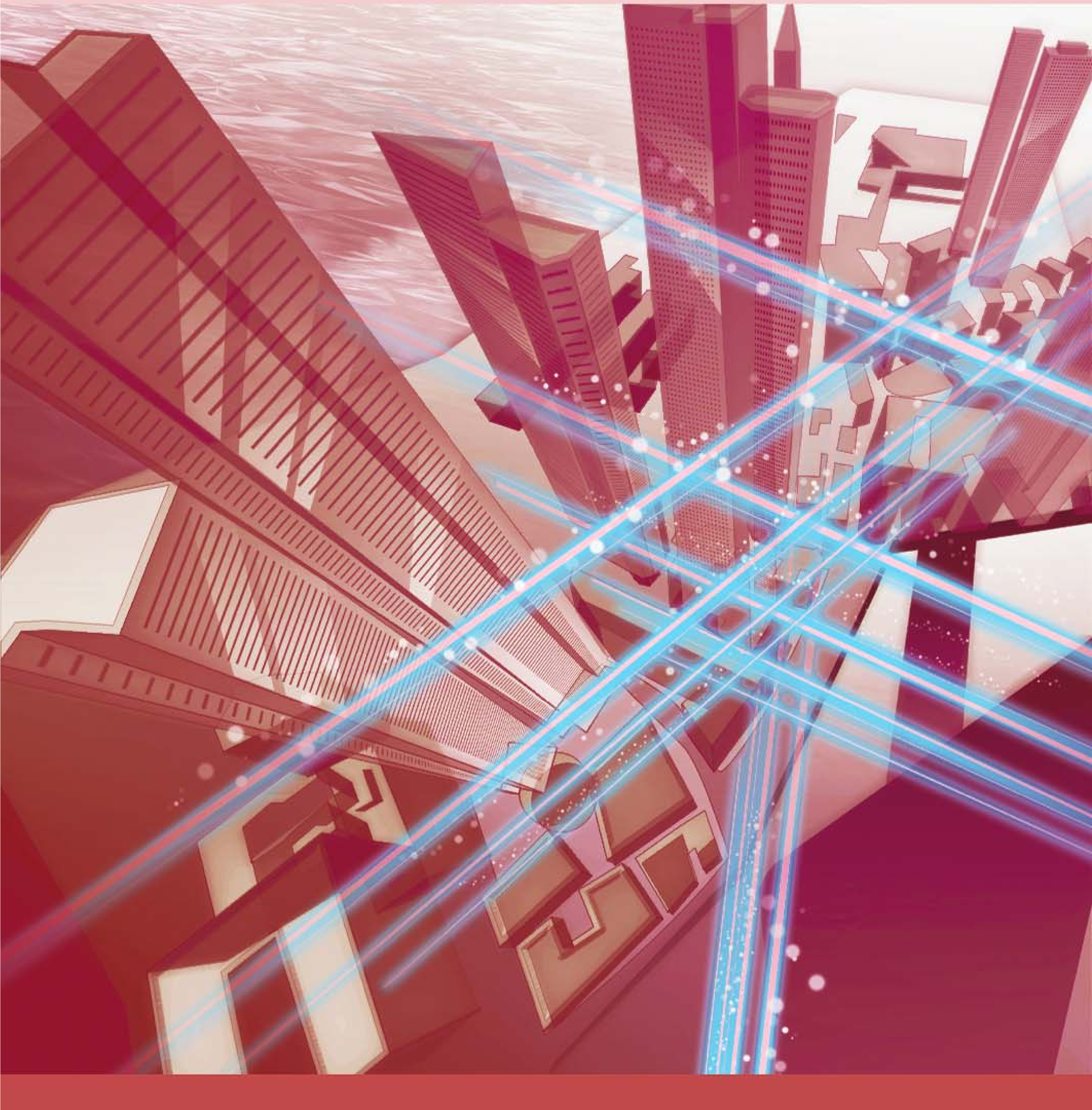

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Multiplying All Opportunities and Ideas in Diverse Fields and Technologies

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Overview

The combined concept of self-transformation and profit growth is gaining momentum in the NTT Group. Based on the B2B2X (business-to-business-to-X) model, the Group is pursuing collaboration with a wide variety of players while taking up important themes such as overcoming social problems and strengthening industrial competitiveness. We asked Hiromichi Shinohara, NTT Senior Executive Vice President, to tell us about the aspirations of the NTT Group for this year and the outlook toward 2020, which is only three years away.

Keywords: B2B2X, artificial intelligence, hitoe

Creating a revolution through collaboration

—Mr. Shinohara, please tell us about this year's goals.

I consider 2016 to have been the year in which the B2B2X (business-to-business-to-X) model began to take shape in the NTT Group. I would therefore like to expand upon this model in 2017.

In last year's B2B2X business, what made me feel our strength the most was our ability to achieve a multiplying effect both inside and outside the company in terms of expanding our business. We achieved this effect not only with outside business partners, but also with the technologies of both the NTT laboratories and the NTT business companies within the NTT Group. We also achieved a variety of multiplying effects among projects within the NTT laboratories. In short, 2016 was a year in which new mechanisms demonstrating the strength of the NTT Group began to evolve just about everywhere.

To give some concrete examples, we have undertaken the standardization of technologies for the FANUC Intelligent Edge Link and Drive system (FIELD system) developed by FANUC Corporation [1]. In this case, we were able to propose new value to FANUC by multiplying the value, achievements, and know-how of the NTT Group, such as the increasingly popular edge computing technologies from the NTT laboratories, application development technologies from NTT DATA, and operations technologies from NTT Communications (NTT Com).

We have also concluded a partnership agreement with KUBOTA Corporation in relation to their infrastructure solutions for agricultural, water, and environmental management with the aim of creating new value for their customers by multiplying NTT's research and development (R&D) achievements and the features of eight NTT Group companies including NTT Com, JSOL, and HALEX [2].

In this way, by extracting and multiplying the strengths and features of each NTT Group company while sharing major objectives, I believe that we can become an even stronger enterprise that can contribute to the prosperity of a wide variety of customers.

In addition to the above, we have also set our sights on merging traditional arts such as Japanese kabuki with information and communication technology (ICT), as unusual as that might seem [3]. When viewing ICT as systems, functions, and services, it's easy to imagine the forms that it can take. When using ICT in the world of traditional arts, however, it may be difficult to identify or imagine. To further enhance the value of traditional arts and to make them more accessible to a broad audience, we have been deepening our knowledge of how best to use ICT with the traditional arts and searching out effective methods in consultation with various partners.

—The power of multiplying seems to increase all the more by interconnecting a variety of industries.

I believe that there are many fields in addition to the ones I just mentioned in which we can make good use of ICT through this multiplying effect, and I want to expand into those fields from here on. To this end, we need to clarify how best to combine the strengths in the NTT Group when collaborating with key players in industry. What we cannot forget here is the value that lies in close collaboration within the NTT Group.

A typical example of collaboration within the NTT Group can be found in the field of artificial intelligence (AI). To accelerate development in this field, the NTT Group launched its corevo™ initiative last year to leverage its wide array of AI-related technologies nurtured by R&D [4]. The reasoning behind setting up corevo as a group-wide brand was to prevent the generation of dispersed losses that occur through separate efforts (wasted development expenses, slow development, etc.) and to pursue enhanced convenience for customers above anything else.

NTT Group companies have been using corevo to expand and study services. NTT EAST, for example, has begun to offer cloud-type robot services in the field of nursing care in cooperation with a robot manufacturer. In addition, NTT WEST has begun field trials of Smart HIKARI Golf that uses "hitoe" wearable sensing fabric [5] to analyze a golfer's biological data such as heart beat during play and to visualize the player's mental state. NTT Com, meanwhile, has succeeded in automatically detecting dangerous automobile driving using AI and has begun

studies on commercializing this technology. Moreover, NTT DOCOMO has been performing joint experiments with the Tokyo Musen Cooperative Association on making taxi dispatching more efficient by providing drivers with taxi-use demand prediction data for 30 minutes out. NTT DATA, for its part, has begun to provide an anomaly noise detection solution to support anomaly detection and preventive maintenance in industrial fields by visualizing the operating sounds of equipment and devices using Internet of Things technology.

The NTT laboratories are also playing a major role in the NTT Group's expansion into diverse fields. In the field of retail, joint experiments have begun with 7-Eleven convenience stores on a mechanism for obtaining product information by simply pointing a smartphone over a display case. Additionally, thanks to revision of Japan's Pharmaceuticals and Medical Devices Act (governing the quality, effectiveness, and safety of drugs/medicines and medical devices), "hitoe" has begun to be applied for the measurement of user electrocardiograms as a medical device. In the above ways, we are achieving a multiplying effect in a wide range of fields.

At the risk of repeating myself, I would like to magnify this multiplying effect in even more fields in 2017 and thereby raise the morale and spirit of everyone in the NTT Group. When thinking about ICT of the future, we can be sure that collecting data of value and sharing and using it throughout Japan will be of great importance. By applying this multiplying effect to data having all kinds of value in all sorts of fields, I would like to create things of even more value that can be of great use in society and bring joy to many people.

Creating value with ICT to enhance stadium business and athlete empowerment

—The major sporting event coming to Japan is only three years away. How are you planning for this event and for business expansion beyond?

Yes, we of course have initiatives related to the big event of 2020, which we can divide into three main endeavors. The first is welcoming and providing hospitality services to the great number of people that will be coming to Japan from abroad. The second relates to viewing games and events and to athlete empowerment. And last but not least, the third is to create a legacy beyond 2020.

First, to become a good host to foreign visitors, the most important thing is to create and provide convenient and easy-to-use services. The demand for services related to tourism in general has been addressed by government policies too, so we would like to roll out services not simply for the 2020 event but also with a view to aiding all foreign tourists coming to Japan in 2020 and into the future.

Second, in terms of viewing games and events, we want to provide services that promote a sense of enjoyment that is different from anything in the past. In the United States, which can be called an advanced country in the business of sports and stadium operations, the watching and enjoying of professional sports has itself become a business. In Japan, meanwhile, sport is more closely associated with the concept of an athlete working hard and going all out to win. With this in mind, we can consider novel services that can revolutionize the stadium business. For example, spectators purchasing premium tickets could be provided with an ultra-realistic space to enable viewing from the viewpoint of an athlete, while spectators in general seats could be provided with 3D (three-dimensional) athlete-related information on handheld terminals such as smartphones. Additionally, for people who live far away from stadiums, it should be possible to construct viewing environments that everyone can enjoy, such as by offering a highly realistic viewing style at remote venues.

Next, there are still many challenges ahead when it comes to athlete empowerment. There is a group at the NTT laboratories working in brain science, so we can envision athlete training using virtual reality systems and products using “hitoe” fabric that feed the results of measuring and analyzing biological data back to the athlete. In short, we would do well to take up athlete empowerment by providing a supportive environment for sports brain science and athlete training that includes actual collaboration between top-performing players and team staff.

Finally, as to our third endeavor, we attach great importance to developing a robust NTT business toward 2020 that is not simply a passing phenomenon but something that can be passed on to future generations as a legacy of the NTT Group. Here, it is important that everything we undertake on the occasion of the 2020 event be connected to future projects as legacy accomplishments, such as overcoming the language barrier with the many foreign visitors that will be coming to Japan and providing barrier-free environments for visitors with various types of disabilities.

Fortunately, 2020 as a milestone year provides us with a great opportunity to progress beyond the ICT field together with the entire country through a common sense of time along the same time axis. However, whether this three-year span till 2020 is just a short-distance sprint or a long-distance run probably differs from person to person, but for us, it feels more like a short-distance sprint with the feeling of “Time’s running out!” I therefore want to work toward our goals while taking a good look as to what hurdles remain from a technical point of view and how we can construct a structure that can be profitable even after

2020 from a business point of view.

Value created together is for the whole country. Make an effort to raise one's own value.

—What kind of mental attitude is needed to get results when trying to achieve a multiplying effect in diverse fields?

First, with respect to collaboration with a variety of companies and enterprises, I think that nothing will happen until we give it a try. When searching for a partner, both parties may have a sense of "This is it!" when first meeting, and may begin working with each other immediately. In other cases, the other party may have to be persuaded to do something together. While it is necessary to secure a profit for the NTT Group in the short term, it is also important to create new value through collaboration with a variety of partners instead of working to maximize our profit from the very beginning. When the "B" in the middle of "B2B2X" turns out to be multiple companies instead of one, I believe that the multiplying effect of working with those companies will give rise to new value. Furthermore, it's important that we believe strongly that such new value will be of benefit to Japan in the future. While not everything may go well at first, the key is whether a multiplying effect can eventually be achieved with partners that have the same dream and mindset as us. Choosing partners with the same objective in mind can result in a good relationship with common goals over the long term. Unfortunately, there are also times when the result of "multiplying" is simply zero. When working on a collaborative relationship, my advice is to keep track of the tide at all times and be willing to withdraw if conditions deteriorate. Upper management as well must periodically assess the true worth of collaboration.

A big welcome to people who can take a big leap, people with great dreams, and people unafraid of a challenge!

—Mr. Shinohara, can you leave a message for NTT researchers?

I think people doing R&D take great pleasure in leaving a big footprint in society. In this regard, I would like you to write papers of exceptional value. Furthermore, in contrast to simply producing things for society, I would like you to aim for things that can spread throughout society and bring great changes to the way that we live. That is, I would like you to take on big challenges as researchers; please attempt things that even corporate management cannot understand. Take a big leap and show us a world beyond our imagination. My biggest wish is to see all of you take up your daily work with an adventurous attitude and a look of excitement in your eyes. If you should fail or have a difficult time, please feel free to consult with me anytime.

—Finally, what would you like to say to all NTT Group employees?

In the same way, I would like everyone at the NTT Group to have big dreams and pursue challenging work. I would also like each of you to have your own set of principles and evaluation criteria to make sound judgments. Instead of doing something just because someone said so, please think about what was said, find what goal to aim for and the best approach to take, and act according to your own will. If you execute something in the way that someone specified, you will not be able to transcend the goal established by that person. In a company, there are all kinds of managerial positions and viewpoints, but each is associated with a single human being whose knowledge and experience are, of course, limited. It is exactly for this reason that I would like you to act on your own volition while contemplating what was said so that you can leap beyond that framework. I would be happy to meet a person who thinks "outside the box" and behaves in a way that betrays my expectations in a good sense. Indeed, I have great expectations that many people will do amazing things above and beyond what I could ever imagine!

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Interviewee profile

■ Career highlights

Hiromichi Shinohara joined Nippon Telegraph and Telephone Public Corporation (now NTT) in April 1978. In 1998, he was promoted to Vice President of the Information Sharing Laboratory Group at Access Network Service Systems Laboratories. He became Senior Vice President of the Information Sharing Laboratory Group in June 2007. In June 2009, he became a member of the Board of NTT and Head of the R&D Strategy Department. In June 2012, he became Executive Vice President and Head of the R&D Strategy Department. He took up his present position in June 2014.

On Si Platform Opens a New World in AI-IoT Service Era

Tsuneyuki Haga, Akira Okada, and Shinji Matsuo

Abstract

In the near future, ICT (information and communication technology) services are expected to achieve a dramatic evolution through the use of the cloud, IoT (Internet of Things), and AI (artificial intelligence). The communication devices necessary to realize this new era require high performance, high functionality, low cost, and low power consumption. A fusion of various technologies and know-how will be applied in order to meet these requirements. In this article, we explain the concept of an *on Si platform*, which expands upon silicon (Si) photonics, as one solution. We also show the direction of research and development (R&D) of various elemental technologies and describe the R&D fabrication process to realize the on Si platform concept.

Keywords: device technology, transceiver, Si photonics

1. Introduction

The Internet of Things (IoT) is the internetworking of physical devices, vehicles, buildings, and other items that are embedded with electronics, sensors, actuators, and network connectivity that enable these objects to collect data, which are then stored in datacenters. The second-order information obtained by analyzing the real-time data will have great value. In the near future, even this kind of data analysis will be done by artificial intelligence (AI) rather than by people, and this AI will make it possible to create high quality services, bring changes in lifestyle, and boost economic activity.

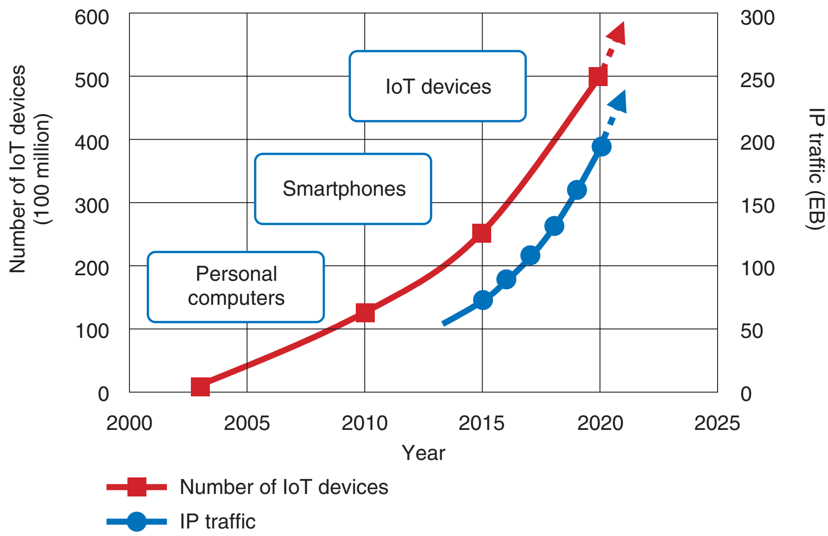
Some of the expected changes in the number of IoT devices and amount of IP (Internet protocol) traffic are shown in **Fig. 1**. Some reports predict that by 2020, at least 25 to 50 billion *things* will have been connected to the Internet [1, 2]. The huge number of things connected to the Internet will lead to an explosive increase in traffic. This will present certain challenges for the NTT laboratories conducting research and development (R&D) on optical devices.

The first challenge concerns the economic element of the increased traffic volume. Mobile traffic, including that of the IoT, is expected to be about 1000 times larger in volume in 2025 compared to 2010, as shown in Fig. 1. Capital investment is necessary in order to meet the demand of the sharp increase in traffic. However, we must avoid passing on the cost to users. Thus, that same 1000-times (or higher) increase in communication traffic must be implemented at lower cost.

The second challenge concerns the size of optical devices. As mentioned above, the traffic volume is expected to be 1000 times larger by 2025. If the size of the optical devices used then is the same as that of the current ones, 1000 times more capacity will be needed for accommodating optical devices, which is not realistic. Therefore, there is strong demand for smaller and more highly integrated optical devices.

The last challenge concerns power consumption. Data collected by IoT devices will be stored in datacenters. However, the power consumption of datacenters in 2018 is expected to account for 3% of total power consumption worldwide. The huge use of power has become a serious problem that needs to be solved on a global scale in order to avoid global warming.

The NTT laboratories are focusing on the use of silicon (Si) platform technologies as the direction of research to solve these challenges in the AI-IoT



*Source:
1. D. Evans, "The Internet of Things - How the Next Evolution of the Internet Is Changing Everything," Cisco IBSG, 2011.
2. Cisco Systems, Inc., "Cisco Visual Networking Index (VNI) Complete Forecast for 2015 to 2020," 2016.

Fig. 1. Number of IoT devices and expected volume of IP traffic.

service era.

2. On Si platform technology

Most electronic appliances such as personal computers and smartphones use electronic devices such as LSIs (large-scale integrated circuits) and integrated circuits (ICs) that contain silicon (Si), one of the most common semiconductors. In the electronic device field, Moore's law states that the integration density of Si ICs doubles every 1.5 years. This tremendous progress is expected to be continued in the fabrication process of Si wafers as the wafer diameter increases. The nanofabrication and high integration of the transistor bring higher device performance and also push down the unit cost of the transistor.

In contrast, most optical devices such as laser diodes (LDs) and photodiodes (PDs) consist of III-V semiconductors such as indium phosphide. With optical devices, nanofabrication and high integration would not necessarily bring high performance and lower cost devices as with electronic devices. Optical devices are fabricated on smaller III-V semiconductor-based wafers, and elements such as the LDs and PDs are each assembled with lens or with optical isolators, which increases the assembly cost. The high assembly cost prevents us from developing less expensive and highly integrated devices.

If we could successfully fabricate optical devices by using a similar process to that of electronic devices with the larger Si-based wafers, we could solve the three challenges described above. The NTT laboratories are working on a novel technology called *on Si platform* technology that combines the fabrication process of electronic devices on larger Si wafers with optical III-V semiconductor technology.

On Si platform technology is the concept to achieve ultra-small, low-cost, and low-power-consumption devices compared to previous optical devices. The proposed technology (**Fig. 2**) is a fusion of the fabrication techniques used in the fields of electronic devices and optical devices that NTT laboratories have developed up to now. This technology enables us to fabricate devices with greater economic efficiency (low cost) that also have a level of functionality and performance that cannot be realized using only Si-based materials by integrating optical and electronic devices on a Si wafer.

Much research has been done throughout the world in an attempt to produce a low-cost optical device and ultimately realize an optical circuit (Si photonics) by using the manufacturing method used in the field of electronic devices. However, the fusion of Si photonics and optical semiconductor technology that provides the laser and the receiver has not yet reached a satisfactory state. Therefore, the NTT laboratories are

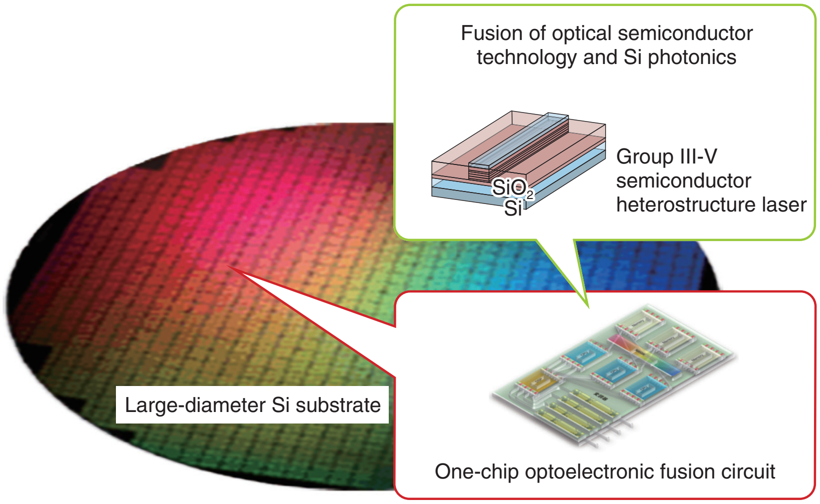
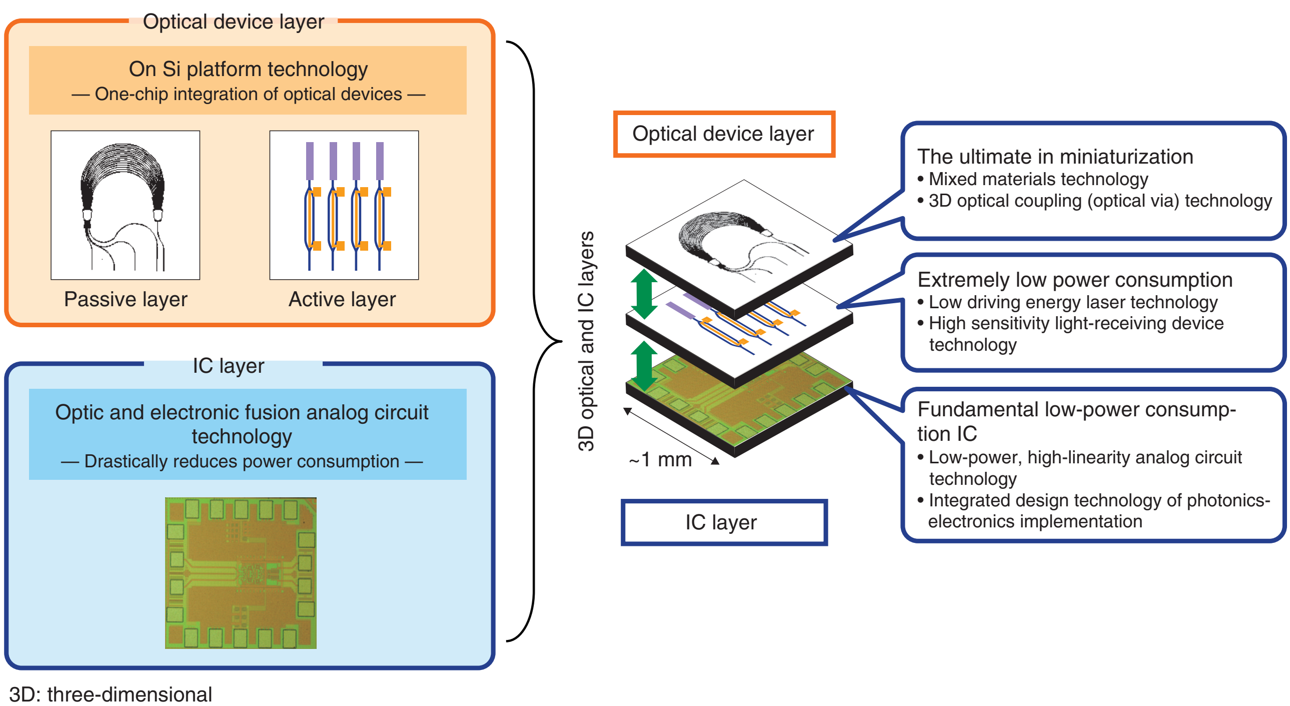


Fig. 2. Concept of on Si platform.



3D: three-dimensional

Fig. 3. Image of 1-mm^2 transceiver chip configuration.

trying to develop a Si platform by accumulating know-how of semiconductor crystal growth and process technologies and by extending Si photonics.

An example of on Si platform technology developed as a proof of concept in the NTT laboratories is a 1-mm^2 transceiver chip, as shown in **Fig. 3**. This ultimate device integrates functions for both transmitting and receiving data within a tiny area. Although it is difficult to integrate all functions within 1 mm^2, we nevertheless refer to this device as a 1-mm^2 transceiver, as we are optimistic that it will be realized.

This 1-mm^2 transceiver consists of three layers and uses stacking technology. The first layer is a passive layer that can perform the splitting, demultiplexing, or phase control of the light on a Si wafer. The second one is an active layer that includes the LDs with extremely low power consumption. The third one is the IC layer that controls optical devices such as the LDs and PDs. Stacking technology is used to integrate the electrical and optical binding into a three-dimensional (3D) configuration.

Many challenges are involved in each layer to realize the 1-mm^2 transceiver. In the passive layer, a technique to form a light coupling in the vertical direction (optical via) is necessary in order to avoid the limitations of size. In the active layer, very low power consumption should be achieved without any optical degradation. In the IC layer that controls the optical devices, even though the previous electronic circuits were designed to have general versatility, a total redesign of the electronic and optical devices is needed in the 1-mm^2 transceiver. Furthermore, the propagation distance of the high-speed signal to be integrated into the 3D configuration needs to be shorter. This will result in lower cost and more compact devices while improving the performance.

3. R&D foundry for optical devices in the future

In the electronic device field, production facilities are expensive to build and maintain. The enormous cost can be a drain on the finances of the company that owns them. To avoid such huge costs, economic forces have led to the existence of many companies that only design devices, which are called *fabless* semiconductor companies, as well as foundries that only manufacture devices without designing them. In the field of Si photonics devices, some foundries that only manufacture optical devices have already started operations, as in the electronic device industry.

However, in the optical device field, production systems are not well equipped. In particular, foundries that can manufacture wafers consisting of Si material and the compound semiconductors used in LD and PD fabrication have not yet been established. Therefore, the NTT laboratories aim to play a key role in Japan, and even in the world, as an R&D foundry for optical devices consisting of Si photonics, compound semiconductors, and electronic devices. To support the R&D, we are steadily accumulating and preparing for the fusion of a variety of technologies and knowledge for the coming AI-IoT service era.

4. Future development

As described in this article, on Si platform technology using extremely small, low cost, and low power devices is expected to open the door for new AI-IoT services. To address the three issues mentioned in section 1, the NTT laboratories are promoting the development of this technology and planning for a timely release on the market of the devices developed using it. The Feature Articles in this issue introduce the recent progress in basic element technologies to realize a 1-mm^2 transceiver by using on Si platform technology. Specifically, the articles introduce optical waveguide technology for ultra-compact, high-density integration [3], LD and PD technology for low power consumption and miniaturization [4], and ultra-low-power analog IC technology [5].

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He received a B.E. and M.E. in electrical engineering from Kyoto University in 1987 and 1989. He joined NTT LSI Laboratories in 1989. He has been engaged in R&D of X-ray and extreme ultraviolet lithography using synchrotron radiation. He was a visiting scientist at the Center for X-ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA, USA, from 2000 to 2001. He received the Young Scientist Award for the Presentation of an Excellent Paper from the Japan Society of Applied Physics (JSAP) in 1996.

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Recent Progress in Optical Waveguide Technologies Enabling Integration of High-density Compact Photonics

Kei Watanabe, Yu Kurata, Tatsurou Hiraki, and Hidetaka Nishi

Abstract

The Internet of Things is expected to lead to the generation of various services in the near future and to bring changes to society. There will be a strong need for optical devices in order to achieve higher traffic capacity, greater economy, and compactness in future optical communication networks. This article reports the recent progress in the optical waveguide technologies being developed to meet these needs.

Keywords: silica based, PLC, silicon nitride waveguide, plasmonics

1. Introduction

In addition to the recent spread of fiber-to-the-home services and the use of smartphones, the practical application of the Internet of Things (IoT) technology, in which everything is connected to the Internet, is expected to enrich society and provide a higher level of services.

The optical network necessary to realize such a society requires circuits that enable various functions by processing light without converting it to electrons. These functions can be attained by using optical waveguides that pass light, as shown in **Fig. 1**. We can design various optical waveguides according to the required functions based on optical waveguide theory. These functions include switching the paths of light (optical switches), separating light into different colors, and bundling different colors into one (light filters). The waveguide functions are determined by the design, but the size of the waveguide and its optical properties are determined by the waveguide material.

The relationship between the minimum bending radius and the relative refractive index difference of optical waveguides is plotted in **Fig. 2**. The relative refractive index difference is the ratio of the difference in the refractive index between the core into which the light is guided and the cladding that covers the core. As the relative refractive index difference increases, the minimum bending radius is reduced. This means that optical devices can be made more compact when we use materials that have higher refractive indices as waveguides. In the electronic device field, miniaturization and high integration of transistors have lowered the unit price of transistors in line with Moore's law, while simultaneously increasing their performance. However, in the optical device field, the simple downsizing of optical devices using materials with a high relative refractive index difference may not always lead to improved performance because of their sensitivity to processing accuracy. There is generally a trade-off between the optical performance and the size of optical devices, and this trade-off prevents us from developing more

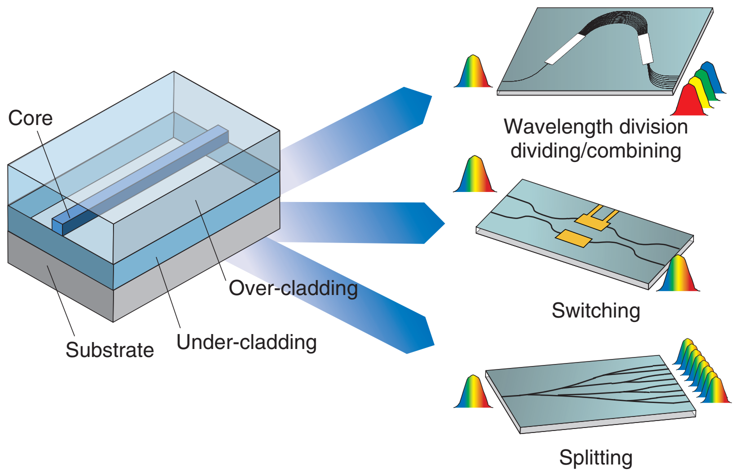


Fig. 1. Types of optical waveguides.

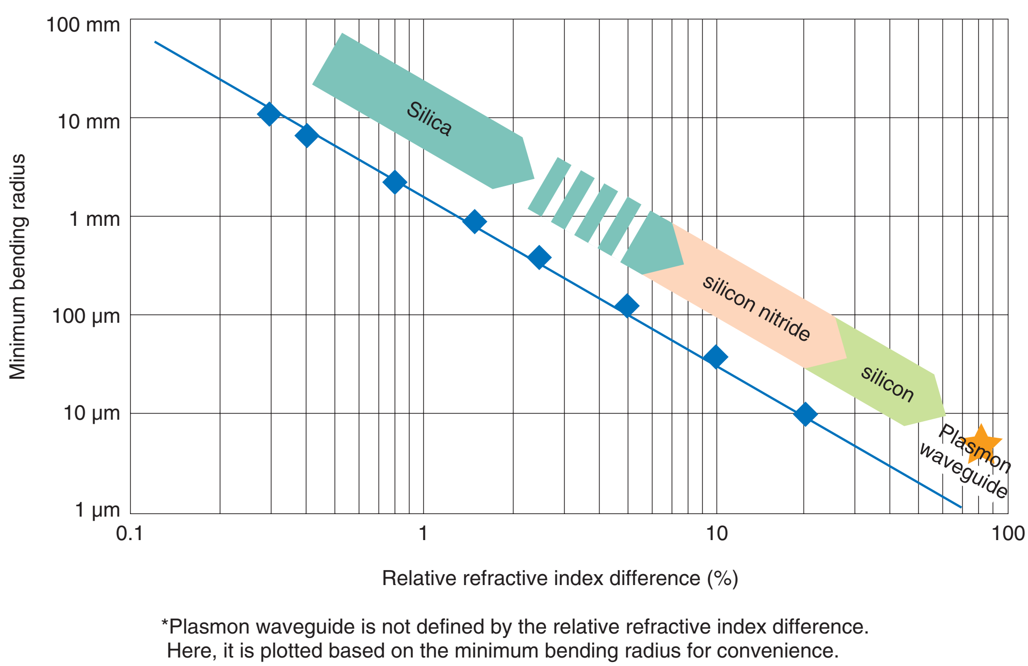


Fig. 2. Relationship between relative refractive index difference and minimum bending radius.

highly integrated optical devices.

NTT laboratories are working to overcome this trade-off by trying to integrate appropriate materials and the refractive index difference into one optical device according to the application. In this article, we report on the recent progress made in optical waveguide technologies that is helping to achieve extremely compact and highly integrated optical devices. We describe four waveguide technologies in detail: high-performance silica-based planar lightwave circuit (PLC) technology, novel low loss silicon nitride (SiN) waveguide technology, plasmon waveguide technology that enables the fusion of electronic and optical devices, and three-dimensional optical via technology that enables the development of optical devices with the ultimate size.

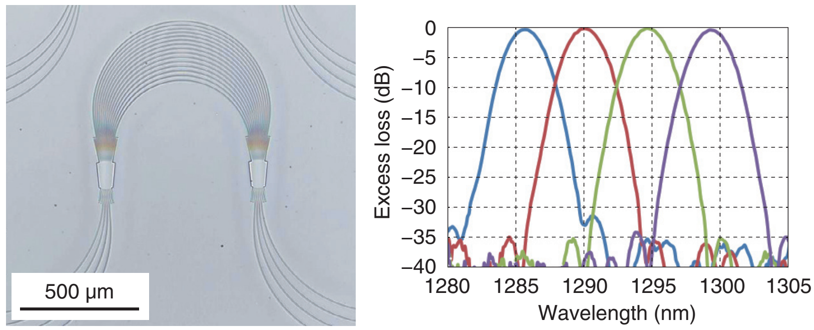


Fig. 3. Compact low-loss AWG.

2. Progress in silica-based PLCs

Silica-based PLCs are optical circuits made of quartz glass, which is the same material as that used for optical fibers. Therefore, silica-based PLCs have excellent characteristics such as low-loss coupling with optical fibers and long-term reliability. Silica-based PLCs can precisely control light-propagation characteristics because of their low relative refractive index difference. Consequently, they are suitable waveguide platforms to achieve high-performance optical filters such those for as arrayed waveguide gratings (AWGs) that split and combine optical signals of different wavelengths.

Several kinds of silica-based PLCs with these advantageous features have been widely introduced into optical communication networks. Commercially available silica-based PLCs have a minimum bend radius of about 1 mm (a relative refractive index difference of 1.5%) at present, and the size of general AWGs is 20–30 mm. We have increased the precision of waveguide fabrication and developed integration techniques that considerably reduce the chip size while maintaining the excellent properties of PLCs. A micrograph and transmission spectra of a precisely fabricated AWG with an increased relative refractive index difference of 5% are shown in **Fig. 3**. We achieved an AWG main optical circuit only 1 mm^2 in size, as well as a low excess loss of only 0.2 dB with this AWG, which is comparable to commercially available AWGs.

3. SiN waveguide

Silicon (Si) nanowire waveguides, whose refractive index difference between the core and clad (delta) is ~40%, are useful for achieving ultra-small photonic-integrated circuits (PICs). However, there are several unresolved issues in fabricating high-performance optical devices using Si-nanowire waveguides. One of the key issues is in fabrication-error tolerance. For example, tolerable fabrication error is on the order of angstroms in order to meet the telecom-grade performance requirements of AWGs with Si-nanowire waveguides. This tolerance is not acceptable even if we use state-of-the-art fabrication technologies.

SiN waveguides, whose delta (~20%) is between those of Si and silica, are promising candidates to maintain high fabrication tolerance with the relatively high integration. In particular, SiN waveguides formed by low-temperature plasma-enhanced chemical vapor deposition (PECVD) have attracted attention because they enable monolithic integration with modulators and detectors without causing thermal degradation. However, the conventional SiN waveguides formed by PECVD have large absorption loss in wavelengths around 1500 nm. This absorption is caused by the N-H bond, which is formed in the film by incorporating hydrogen dissociated from the silane (SiH_4) gas source of the PECVD.

To overcome the issue, we developed a hydrogen-free PECVD method by using a deuterated SiD_4 gas source. The measured transmission spectrum of SiN waveguides (core size: 0.55 × 1.1 μm) formed by using the SiD_4 gas source is shown in **Fig. 4**. The absorption peak at the wavelength around 1500 nm is much less than that of the conventional SiN waveguide formed by using SiH_4 gas (red line). The propagation loss is 1.2 dB/cm, which is low enough to fabricate the PICs used in all telecommunications wavelengths. Note that Si, silica, and SiN waveguides can be monolithically integrated by forming spot-size converters using SiN waveguides. We are using this technology in attempts to fabricate high-performance

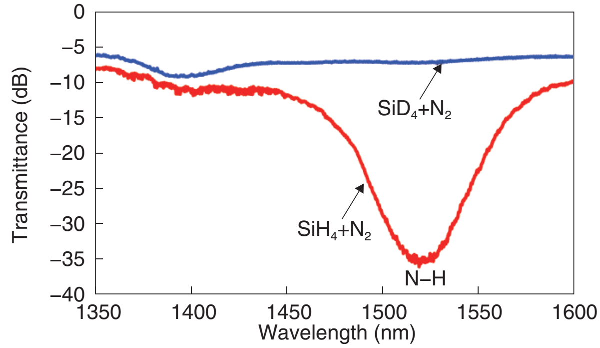


Fig. 4. Measured transmission spectrum of SiN waveguides.

PICs with various types of waveguides on Si photonics platforms.

4. Plasmonic waveguide

Si photonic devices have been attracting a great deal of attention as a promising technical basis for photonics-electronics convergence because their material varieties and fabrication processes are similar to those for Si electronic devices. In terms of device size, Si-nanowire waveguides have a much smaller cross section compared with legacy silica waveguides. Namely, the dimensions of Si-nanowire waveguides are typically several hundred nanometers, and they have 1/100 to 1/1000 the cross-sectional area of the legacy waveguides. However, the channel size of Si transistors has recently reached several tens of nanometers. Thus, there is still a one order of magnitude difference in the Si structure.

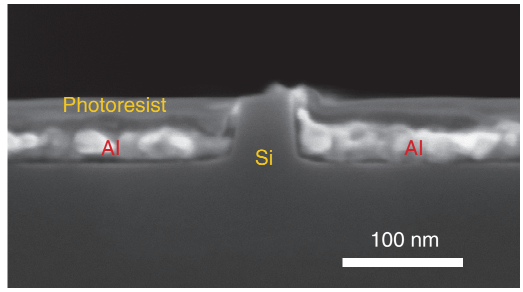
We have developed plasmonic waveguide technologies [1] to further reduce the size of photonic devices. A plasmonic waveguide utilizes surface plasmon-polariton oscillation at metal-dielectric boundaries in order to obtain tight optical confinement within dimensions of several tens of nanometers. We can overcome the issue of the difference in size between photonics and electronics by using this waveguide as a base for optical devices. In addition, such tight optical confinement not only provides us with the advantage of a reduced device size but also several other advantages that improve optical-device performance. For example, some modulators utilizing the electro-optic effect have exhibited enhanced modulation efficiency as the electric-field intensity increases, which has led to reduced operational energy.

A scanning-electron micrograph of a cross section of a fabricated plasmonic waveguide is shown in **Fig. 5(a)**. It has an aluminum (Al)/Si/Al structure, and the Si core size is 60 × 60 nm. The transmittance spectra of fabricated plasmonic waveguides with various lengths are shown in **Fig. 5(b)**. We confirmed an optical propagation loss of 4 dB/μm at 1550 nm, and we think the propagation loss can be reduced to less than 1 dB/μm by improving the fabrication process. Of course, this waveguide has higher loss compared with Si waveguides. In the future, we intend to explore the best-mix configuration with conventional dielectric photonic waveguides with the aim of achieving ultra-small, low-power-consumption opto-electronic systems for short-reach communications.

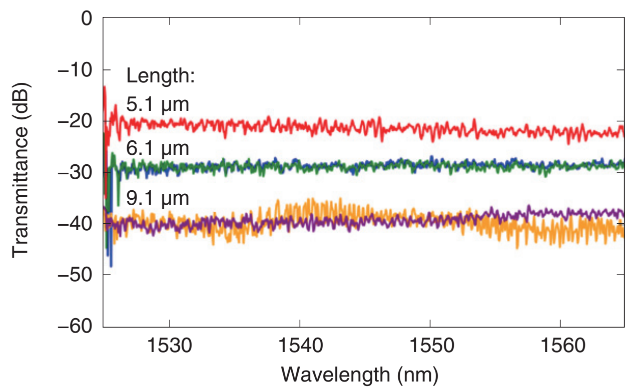
5. Optical through-hole-via technology using mirrors

There are two ways of integrating high-density optical waveguide devices. One way is to reduce the bending radius of waveguides by using waveguides with a high relative refractive index difference. The other is to stack (pile up) the optical circuits. Moreover, when we stack the optical circuits, it also becomes easy to integrate optical circuits with different functions that involve the use of different materials. Of course, the circuits do not work as optical circuits if they are just stacked; it is necessary to couple them optically for each stacked layer. We call this configuration an optical through hole via (*optical via*), where the optical couplings function between different stacked optical layers.

In particular, the path of propagating light in some layers is vertically changed toward other layers, and it is horizontally changed so that light propagates in the other layers when it reaches them with the optical



(a)



(b)

Fig. 5. Fabricated plasmonic waveguide and transmittance spectra.

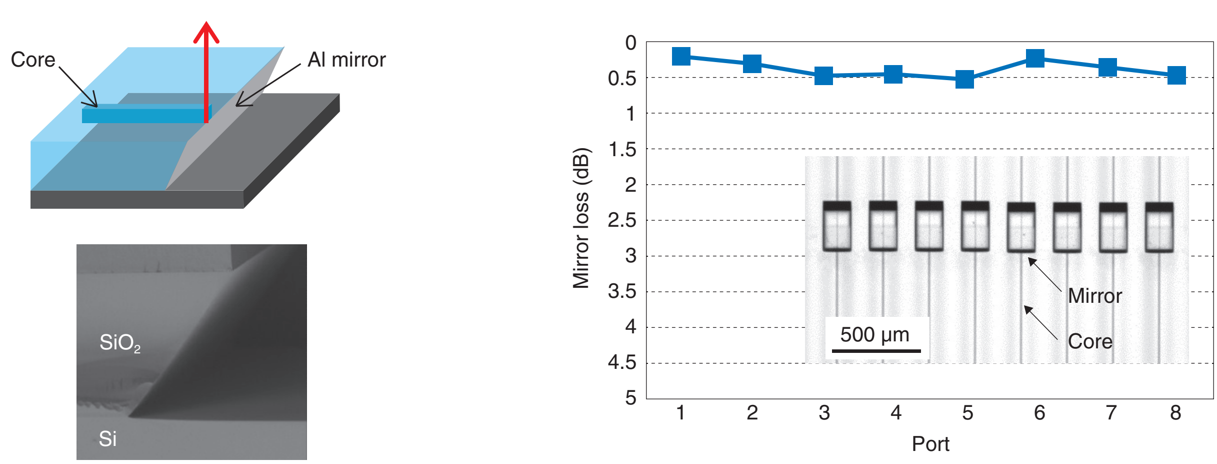


Fig. 6. Mirror for optical via technology.

via function. The technique of vertical light path conversion will become important when we can fabricate optical vias.

We investigated how to achieve such light-path changes using mirrors at NTT Device Technology Laboratories. Mirror losses of fabricated eight-channel mirrors that indicate losses due to light-path changes are shown in **Fig. 6**. We confirmed low-loss light-path changes of less than 0.5 dB, which means the optical coupling loss between two layers was less than 1 dB. Therefore, our mirrors are promising for achieving low-loss optical via technology.

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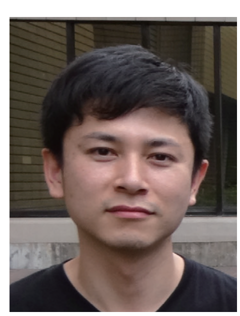

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Compact Optical Devices with Low Power Consumption

Wataru Kobayashi and Masahiro Nada

Abstract

At NTT Device Technology Laboratories, we have been developing an optical transmitter that can improve energy efficiency and emit an optical signal at the same intensity level with half the previous power consumption. We have also been developing an optical receiver that improves the minimum optical received power with the same signaling rate. This can provide us with long distance transmission without an optical amplifier. In this article, we introduce an optical transmitter and an optical receiver with functions for respectively changing an electrical signal to an optical signal and an optical signal to an electrical signal.

Keywords: compound semiconductor device, AXEL, APD

1. Optical transmitter

An optical transmitter in an optical network system changes electrical signals to optical signals. The recent increase in data traffic has inevitably increased the power consumption of optical network systems. Therefore, optical transmitters need to be more energy efficient.

Generally, an optical transmitter has two functions. One is to emit light, and the other is to modulate light, which means converting an electrical "0" and "1" signal to an optical signal. There are two main ways of modulating light. One is to modulate the intensity level of the optical power, and the other is to modulate the phase of the optical signal. An electro-absorption (EA) modulator integrated distributed feedback (DFB) laser (EA-DFB laser) is widely used as an optical intensity modulated laser.

At NTT Device Technology Laboratories, we proposed a semiconductor optical amplifier assisted extended reach EA-DFB laser (AXEL) to greatly reduce the power consumption of an EA-DFB laser [1]. The concept of the AXEL is shown in **Fig. 1**. A conventional EA-DFB laser (Fig. 1(a)) supplies a large injection current to the DFB laser section to increase the intensity of the emitting light, but most of the power of the generated light is lost because of the insertion loss of the EA modulator. This means that most of the supplied power consumed by the EA-DFB laser is used to compensate for the loss at the EA modulator section, resulting in poor energy efficiency.

In contrast, an AXEL can improve the energy efficiency by dividing the DFB laser section into two parts: one for generating light and the other for amplifying modulated light, as shown in Fig. 1(b). Therefore, we can configure the EA-DFB laser while suppressing the effect of the insertion loss of the EA modulator section and achieve energy-efficient operation with this configuration.

Eye diagrams, the modulated output power, and the power consumption of the AXEL and an EA-DFB laser when the power consumption is nearly equal are shown in **Fig. 2**. The AXEL can provide us with transmission through a 100-km single-mode fiber thanks to its improved optical power. Here, the wavelength of the AXEL is 1.55 μm. The advantage of the AXEL is that it can emit modulated light at the same intensity level with half the power consumption and provide a 3-dB increase in modulated optical power with the same power consumption.

Silicon (Si) photonics is currently considered an attractive candidate for the next-generation optical transmitter. The required optical power varies with the required transmission distance, but the concept of

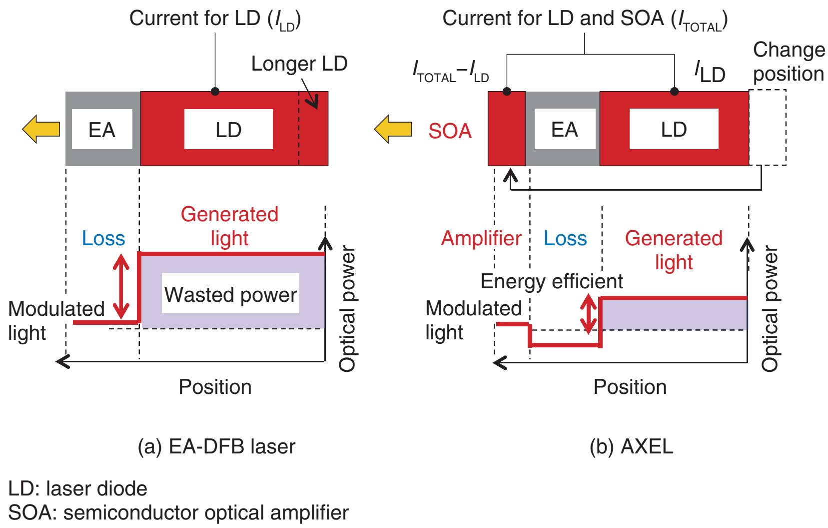


Fig. 1. Concept of AXEL.

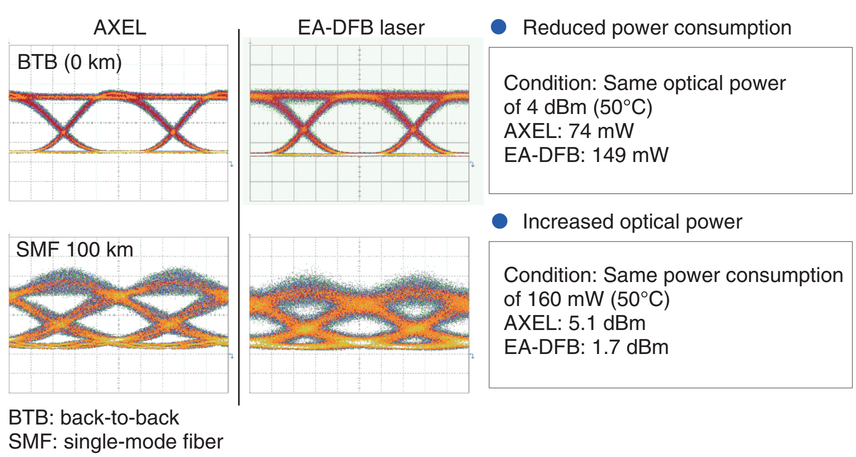


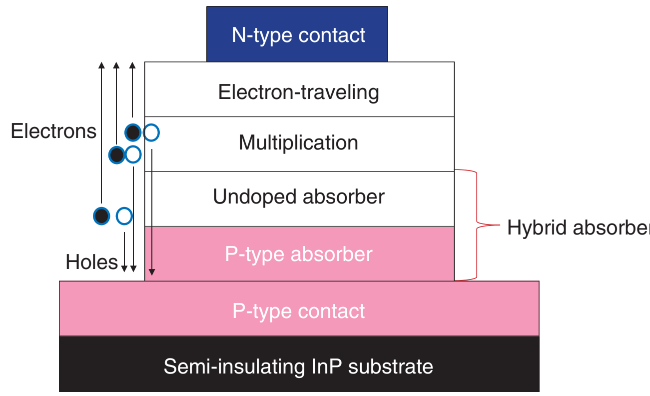
Fig. 2. Advantages of AXEL.

the AXEL can be applied to a wide optical power range, and therefore, we also expect the AXEL to be employed as an optical light source in Si photonics.

2. Optical receiver

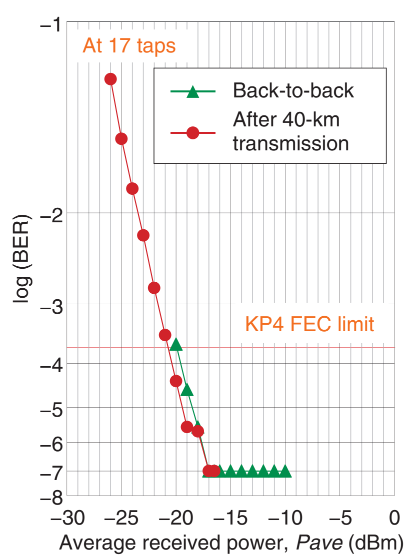
An optical receiver converts an optical signal launched from a laser to an electrical signal after the optical signal has passed through some waveguides and optical fibers. For efficient conversion, the optical receiver must have high sensitivity because the intensity of the received optical signals weakens due to certain losses in the waveguides and optical fibers. We have developed high-speed and high-sensitivity optical receivers and photodetectors for long-haul transmission [2]. Conventional photodiodes (PDs) made with semiconductors consist of p-type and n-type contact layers and an absorption layer. An optical signal injected into the PDs is converted to electrons and holes in the absorption layer.

In contrast, an avalanche photodiode (APD) provides higher sensitivity than PDs. This is because it contains a multiplication layer in addition to the conventional PD structure. In the multiplication layer, secondary electrons and holes are produced by bombarding atoms with accelerated electrons and holes.



InP: indium phosphide

Fig. 3. Schematic view of APD.



BER: bit error rate
FEC: forward error correction
NRZ: non-return-to-zero

Fig. 4. Bit error rate of APD-based optical receiver at 56-Gbit/s NRZ signal.

The successive generation of secondary electrons and holes in the multiplication layer results in the amplification of the electrical signals against the weak optical input signals. This is why the APD can provide higher sensitivity than PDs.

A schematic view of the compound semiconductor-based APD developed by NTT is shown in **Fig. 3**. One unique feature of our APD is a hybrid absorber that consists of p-type and undoped absorber layers. The hybrid absorber enables operation at higher speed and with higher sensitivity compared to the conventional absorber. The results of a demonstration of our APD used for 56-Gbit/s, 40-km transmission with a non-return-to-zero signal are shown in **Fig. 4**.

Recent progress in Si fabrication technology has opened the way to large-scale monolithic integration of optical components, including PDs and APDs, along with optical waveguides and modulators. Since our approach with compound semiconductor materi-als has an advantage in high-speed and high-sensitivity operations due to the flexibility of device design and material characteristics, merging our technology for high-performance APDs with Si photonics will make it possible to provide more compact optical receivers with higher performance and lower power consumption.

3. Future plans

This article introduced NTT's optical transmitter and receiver technology for future large-capacity optical-fiber communication systems. As the data transmission capacity continues to increase, it will be necessary to further reduce the size and power consumption of optical transmitters and receivers. In the future, Si photonics might make it possible to integrate optical transmitters, receivers, and electrical integrated circuits on the same Si platform. This would contribute to further lowering power consumption and reducing the size of optical transceivers. Our goal is to achieve major breakthroughs in high-speed and low-power consumption optical transmitters and receivers. We are striving to reach this goal by seeking ways to successfully merge Si photonics technology and compound semiconductor device technologies.

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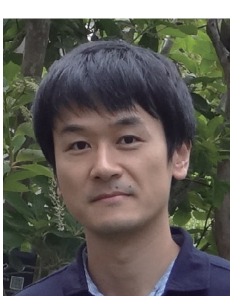

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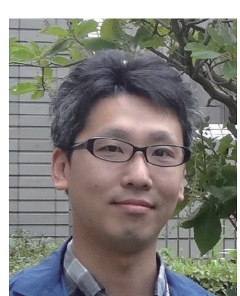

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Very Low Power Analog IC Techniques

Toshiki Kishi, Munehiko Nagatani, Wataru Kobayashi, Minoru Ida, Kenji Kurishima, and Hideyuki Nosaka

Abstract

We are studying the development of very compact next-generation optical transceivers by using integrated design techniques of photonics-electronics implementation. We introduce in this article the techniques used to design analog integrated circuits with very low power for photonics-electronics implementation.

Keywords: integrated design, photonics-electronics implementation, very low power, shunt driving circuits

1. Introduction

Transmission capacity has grown rapidly in recent years, and further rapid increases in capacity are expected in the future with the advent of the Internet of Things and cloud computing technologies. High-speed data communication is needed in datacenters to process large amounts of traffic. However, with the increasing volume of data communication, the scale and power dissipation of datacenters is also increasing. A reduction in the size and power dissipation of optical transceivers is therefore necessary in order to reduce the scale and power dissipation of datacenters. The target power dissipation for a 1-mm^2 optical transceiver is shown in **Fig. 1**.

The transmission capacity of the Ethernet, the main element of the networks, has grown rapidly, and 100-Gbit/s Ethernet has been standardized. In 100-Gbit/s Ethernet, optical transceivers that have an electroabsorption-modulator-integrated laser (EML) and distributed feedback-laser diode (DFB-LD) are used. The module size of conventional optical transceivers is several square centimeters, and power dissipation per data rate is 2–20 mW/Gbit/s. Our goals are to develop a compact optical transceiver module with a size of 1 mm^2 and to achieve a power dissipation per data rate of 0.5 mW/Gbit/s.

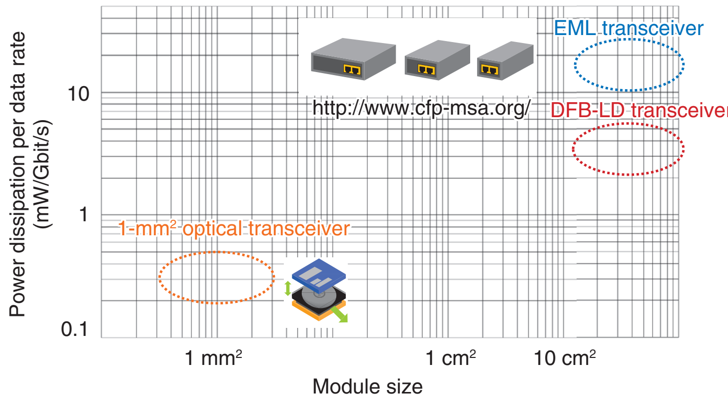
To achieve these goals, we are investigating integrated design techniques for photonics-electronics implementation that take into account the impact of using optical and electrical devices. These design techniques enable the effect of photonics-electronics implementation with optical transceivers to be simulated. In addition, optical waveform simulation can be performed when the designed electrical devices drive optical devices.

In this article, we introduce techniques for designing very low power analog integrated circuits (ICs). These techniques use integrated design techniques of photonics-electronics implementation and are expected to achieve very compact and low power 1-mm^2 optical transceivers [1].

2. Conventional and proposed circuits

A conventional directly modulated laser (DML)-based transmitter front-end is shown in **Fig. 2(a)**. To match the impedance between the LD driver and the LD, an impedance matching resistor is connected to the LD in series. Therefore, extra power is consumed by the resistance. A power-efficient shunt LD driver architecture has been reported to reduce power dissipation [2]. The use of a shunt-driving circuit for the LD driver of a DML transmitter front-end results in lower power dissipation of the front-end compared to the conventional one.

A DML transmitter front-end consisting of the shunt LD driver and LD is illustrated in **Fig. 2(b)**. The



DFB-LD: distributed-feedback-laser diode
EML: electroabsorption-modulator-integrated laser

Fig. 1. Target power dissipation for 1-mm² optical transceiver.

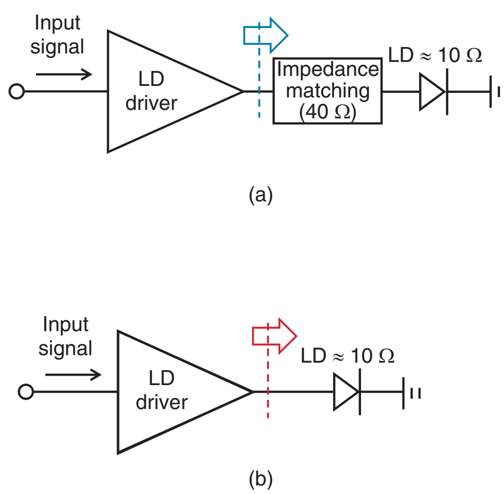


Fig. 2. (a) Conventional and (b) proposed transmitter circuits.

shunt driver was originally used to modulate light-emitting diodes at low speed. However, recent improvements in semiconductor processes enable the shunt driver to operate with high-speed LDs. A DML transmitter front-end consisting of the shunt LD driver does not have an impedance matching resistor. Since the output impedance of a shunt driver is much higher than that of conventional drivers with an impedance matching resistor, the shunt drivers have to be placed as close to the LD as possible to avoid multiple reflections caused by impedance mismatch. Because the transmitter front-end using the shunt driver is implemented with the LD driver and LD as one, the integrated design environment of photonics-electronics implementation is necessary.

3. Integrated design techniques of photonics-electronics implementation

In this section, we discuss the elements of the integrated design techniques in more detail.

3.1 Design environment

We created the integrated design environment of photonics-electronics implementation in SPICE (Simulation Program with Integrated Circuit Emphasis).

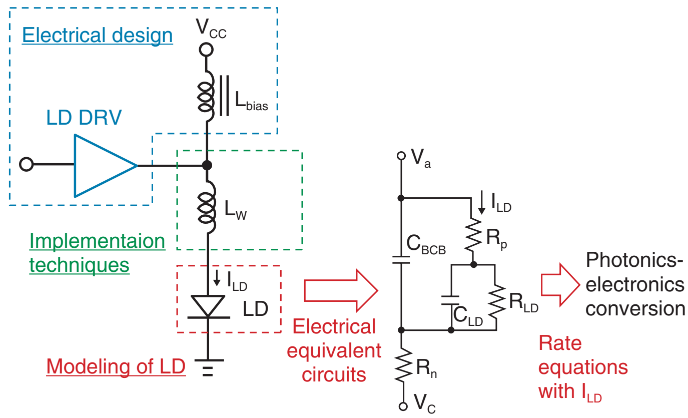


Fig. 3. Integrated design environment of photonics-electronics implementation.

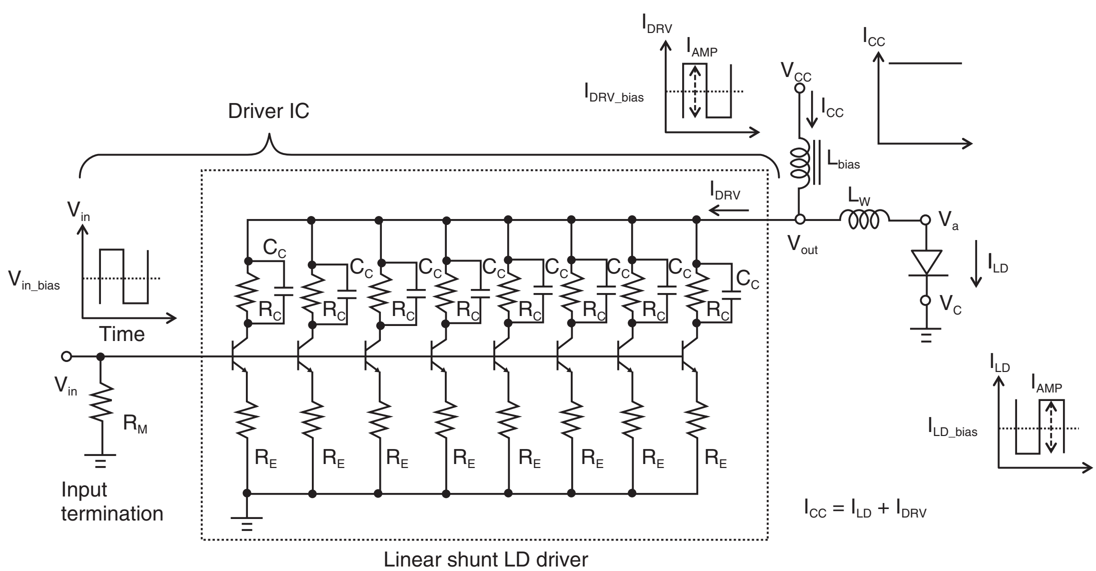
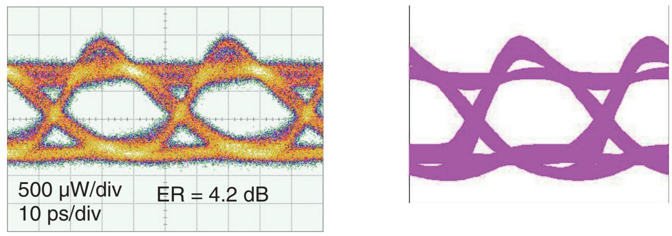


Fig. 4. Very low power LD driver.

The design environment is shown in **Fig. 3** and consists of the electrical design, implementation techniques, and modeling of the LD. In modeling the LD, we first fabricated electrical equivalent circuits of the LD. Then, by inserting the LD current (I_{LD}) of these equivalent circuits into rate equations, we were able to perform photonics-electronics conversion. The use of the integrated design environment of photonics-electronics implementation enabled optical waveform simulation to be performed in SPICE.

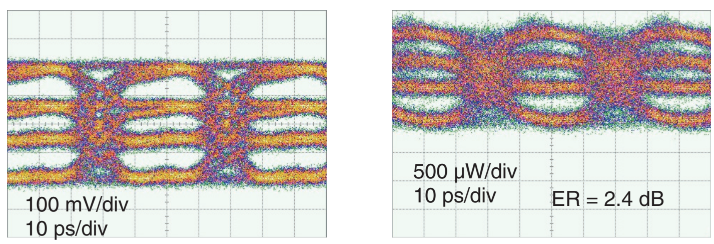
3.2 Very low power LD driver

A diagram of the transmitter front-end with the linear shunt LD driver is shown in **Fig. 4**. In the transmitter front-end, the off-chip inductor is connected to the output terminal of the LD driver in order to apply bias to both the LD and LD driver. The anode terminal of the LD is connected to the output terminal of the LD driver by wire bonding. The inductor is denoted as L_{bias}. The parasitic inductance of the bonding wire is denoted as L_w, and it is about 0.16 nH in the assembly condition. The current provided from V_{CC} (collector supply line voltage) is supplied to both the LD and the shunt driver, and the shunt driver pulls modulation current proportional to the input signal. The higher the input voltage is, the smaller the I_{LD}



(a) Measured optical output waveform (b) Simulated optical output waveform

Fig. 5. 25-Gbit/s NRZ waveforms.



(a) Measured electrical input waveform (b) Measured optical output waveform

Fig. 6. Measured 50-Gbit/s PAM4 waveforms.

becomes. Therefore, the logic of the optical signal is the inverted logic of the input signal.

Because the output impedance of the shunt driver is high, modulation current from the driver is supplied only to the LD. The shunt driver is placed in parallel with an LD, as shown in the schematic of the transmitter front-end with the LD driver. It is configured by a common emitter amplifier with an emitter resistor; therefore, it functions as a linear amplifier. In addition, by connecting the resistor collector (R_C) and common collector (C_C) in parallel between the collector of the transistor and V_{out}, the operating points of the transistors are optimized for high-linearity and high-speed operation. The R_C drops the collector voltage to set operating points of the transistors in the linear operation region. The C_C, which is connected to the R_C in parallel, improves the bandwidth of the LD driver.

3.3 Measured and simulated optical waveforms

The measured 25-Gbit/s NRZ (non-return-to-zero) optical output waveform is shown in **Fig. 5(a)**. The extinction ratio (ER) is about 4.2 dB. In Fig. 5(a), the overshoot of the waveform is probably caused by the frequency of relaxation oscillations of the DFB-LD. Simulated optical waveforms are shown in **Fig. 5(b)**. We first created an integrated design environment of photonics-electronics implementation in SPICE. Then, we carried out the simulation of the optical output waveform. As shown in Fig. 5(b), the simulated optical output waveform is the same as the measured one in Fig. 5(a). The use of the integrated design environment of photonics-electronics implementation made it possible to obtain simulated optical waveforms that were the same as the measured waveforms.

The measured electrical input 50-Gbit/s four-level pulse amplitude modulation (PAM4) waveform is shown in **Fig. 6(a)**. The PAM4 electrical signals are unequally spaced because of the measurement setup for generating input signals. The measured optical PAM4 waveform is shown in **Fig. 6(b)**. The ER is about 2.4 dB. The overshoot of the waveform decreases because of the high LD bias current. Changing the input bias voltage of the driver enables the linearity of the driver to be changed in response to the modulation format of the input signals. The eye openings of the PAM4 optical waveform were measured, and they show a linear response to PAM4 input signals, as shown in Fig. 6(b).

4. Future development

We designed a linear shunt LD driver in order to construct a low-power transmitter front-end that can operate in response to modulation formats such as PAM4. The driver was designed in an integrated design environment of photonics-electronics implementation and fabricated using our indium-phosphide (InP) heterojunction bipolar transistor (HBT) technology (f_t = 290 GHz, f_{max} = 320 GHz). In the future, we plan to design LD drivers using a silicon CMOS (complementary metal oxide semiconductor) process in order to achieve large-scale integrated and very compact 1-mm^2 optical transceivers that have a low power architecture.

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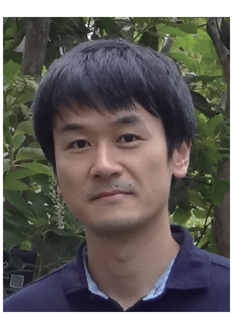

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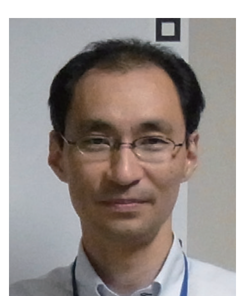

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Directional Remapping in Tactile Motion Perception

Shinobu Kuroki

Abstract

This article introduces tactile illusions in which adaptation to one directional motion alters the direction of the following motion. We used this illusion to explore how the brain calculates tactile motion directions, which is an essential issue in creating tactile navigation systems.

Keywords: tactile, motion, illusion

1. Introduction

Motion perception is a function essential to the lives of everyone. We have a purpose-built mechanism in our brain to detect motion, which is beautifully represented as the well-known *waterfall illusion*; after prolonged observation of a waterfall, an illusory upward motion can be seen in a static cliff (**Fig. 1**). This phenomenon is referred to as the motion aftereffect (MAE) [e.g., 1, 2].

Motion perception holds a prominent position not only in vision but also in touch. The motion between the fingertips and an object has important functions such as preventing a glass from slipping from our hand and making it possible to identify the surface texture of fabrics. However, the mechanism of motion perception in touch has not been fully revealed. In this article, I introduce our group's recent studies on tactile motion perception using the MAE. How tactile motion is processed in our brain is an essential issue in neuroscience, and, at the same time, it can contribute to the development of future user-friendly information technologies.

2. MAE in touch

The MAE has been used to investigate the visual mechanism of information processing in the brain. It provides proof that a certain mechanism exists in the brain without the need for imaging or neurophysiological measurement. The waterfall illusion, the most famous MAE, has been explained as follows. It is widely known that we have neurons that specifically respond to directional motion, and the perceived motion direction can be estimated from the activity valance of neurons responding to each direction. When we watch a waterfall, downward-motion neurons are adapted and become fatigued. Then, the activity of downward-motion neurons becomes weaker than that of the upward-motion ones. When we watch a static field, the activity level of all of the directional neurons is mostly the same. However, after adaptation to the waterfall/downward motion, this balance is violated. The downward-motion neurons cannot fire at the same level as the other directional neurons. In the waterfall illusion, this results in illusory upward motion of the static field, that is, the cliff. Note that occurrence of this illusion itself is proof of downward-motion neurons.

Compared to the visual MAE, which has been repeatedly observed in a robust and rigid fashion [3], the tactile MAE has received far less attention, and its occurrence itself has been a matter of long debate [4, 5]. A breakthrough study was done by Watanabe et al., who introduced a new adaptation method that can induce a tactile MAE in a reproducible fashion [5]. The essence of their method is that they employed motion stimuli with an ambiguous direction as test stimuli instead of using static stimuli such as a cliff. If participants touch static stimuli as test stimuli after adapting to one-directional motion stimuli, as in the conventional manner, they first judge whether the test

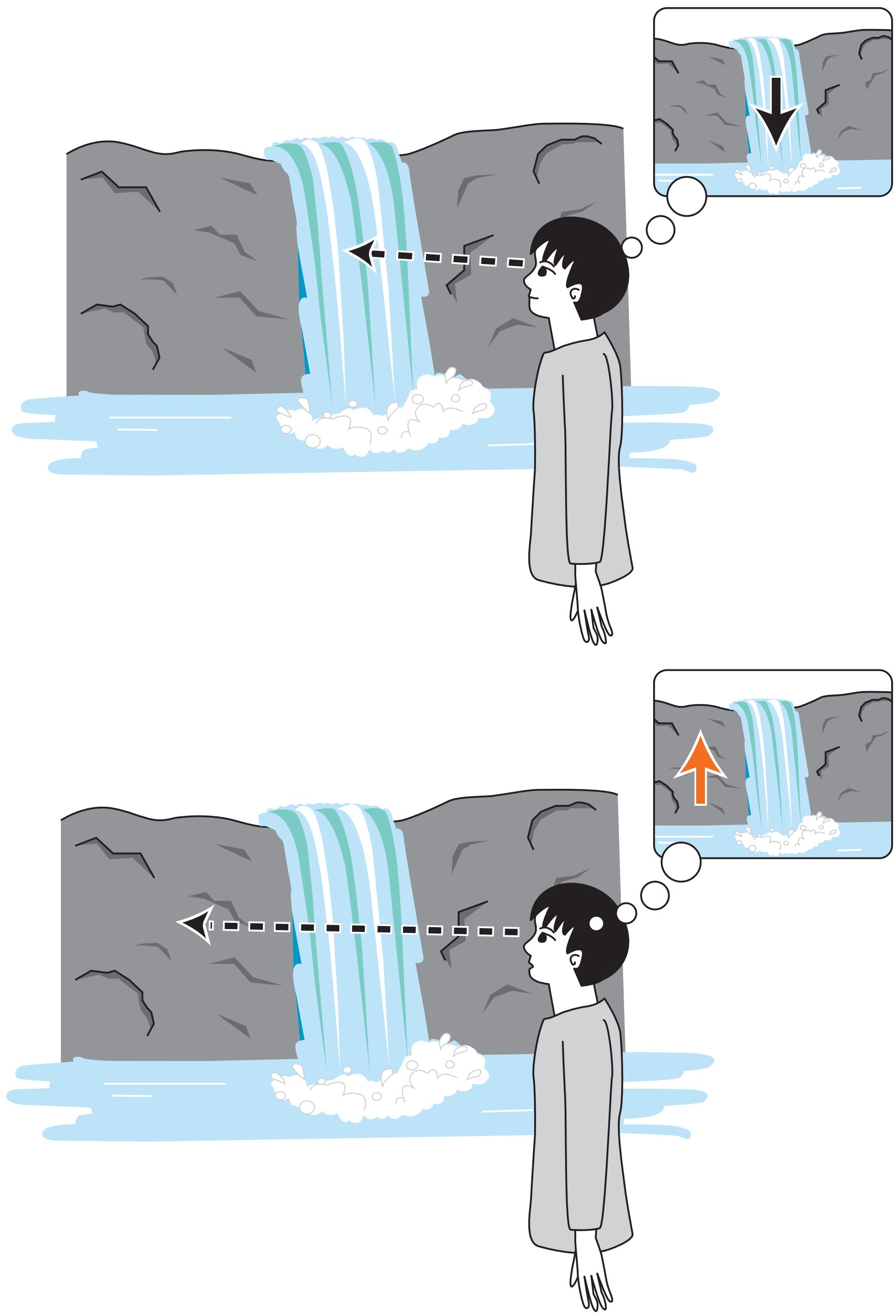

Fig. 1. Waterfall illusion. After prolonged observation of a waterfall (top panel), an illusory upward motion can be seen in a static cliff (bottom panel).

stimuli are moving or not then report the perceived direction of the motion. On the other hand, if participants touch dynamic stimuli as test stimuli, they report the perceived direction based on their ambiguous perception. Only in the latter case can a robust MAE—illusory motion in the direction opposite to the adapted motion—be observed in touch.

Watanabe et al. used pin-shaped vibrators to generate a sensation of apparent motion on the finger cushion. Pins were vertically vibrated (pushed onto and pulled off the skin surface) at a frequency of 30 Hz by vibration generators (EMIC Inc., Kyoto, Japan,

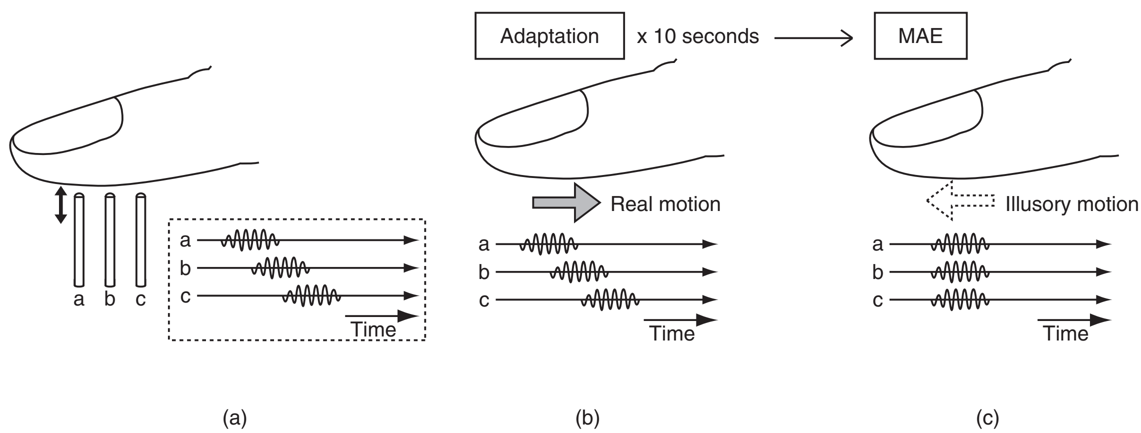

Fig. 2. Experimental setup in [5] and schematic diagram of tactile MAE. After prolonged perception of motion to the palm (adaptation panel), an illusory motion to the nail can be perceived with a directionally ambiguous motion (MAE panel).

511-A). When three pins were sequentially driven, the participant perceived apparent motion on the finger cushion. For example, when the nail-side pin stuck out first, then the middle pin, and finally the palm-side pin (**Fig. 2(a)**), participants perceived palm motion on the finger pad. With such stimuli, when participants adapted to one direction, say, to the palm motion for tens of seconds (**Fig. 2(b)**, adaptation phase), they tended to report directionally ambiguous motion as a motion to the nail (**Fig. 2(c)**, MAE phase).

Watanabe et al. conducted tactile adaptation experiments under several conditions and successfully showed the MAE for straight motion within the finger pad, straight motion from the finger base to tip, and circular motion within the finger pad. These results suggest that the MAE can be a useful psychophysical tool for probing the neural mechanisms of tactile motion processing, as well as that of visual motion processing. This finding supports the possibility that tactile motion processing shares neural circuits with visual motion processing, which is good news for scientists since visual mechanisms are much better understood than tactile ones. In addition, the tactile MAE enables us to consider a tactile-specific issue—how the tactile motion can be processed in conjunction with kinesthetic information such as finger position and posture. I discuss this point in the next section.

3. MAE across fingers

In touch, direction is an issue. The input on the skin is encoded by the sensors underneath it. Therefore, for the sensors, it feels like the direction of motion on the fingertip is from the palm to the nail. Instead, we usually perceive tactile motion defined in an environmental coordinate, such as upward or rightward. This means that the brain needs to transform the motion direction on the skin coordinate into the direction on the remapped environmental coordinate while taking body posture into account. The same issue arises in vision and audition regarding the retina-/ear-centered coordinate vs. the environmental coordinate. However, touch has more layered remapping processes involving skin-, hand-, arm-, and body-centered coordinates since we can drastically change our body posture at many stages. Thus, remapping in touch must pose a difficult problem to our brain.

What will happen if we change our posture after adaptation? Will the MAE occur according to the skin coordinate or to the environmental coordinate? MAE that occurs according to the skin coordinate would mean that tactile directional neurons might exist in the first stage of cortical processing, where cutaneous sensors encoding skin input and kinesthetic sensors encoding posture information are independently represented. In contrast, MAE that occurs according to the environmental coordinate would suggest that the neurons exist after the integration of cutaneous and kinesthetic sensors. To test these possibilities, we examined whether finger posture modulates the direction of the tactile MAE induced by an apparent inter-finger motion between the index and middle fingers [6].

In the experiment, we introduced conflict between

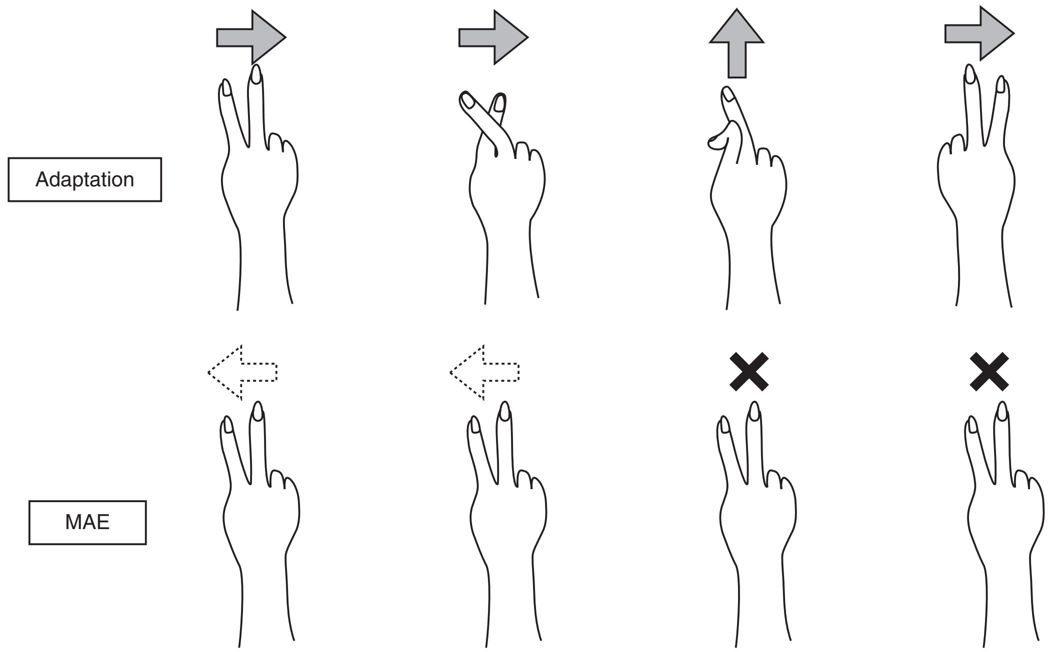

Fig. 3. Schematic diagram of MAE across fingers observed in our study [6]. When participants adapted to one directional motion for a while with their finger posture shown in the top images, they tended to report direction-ambiguous test stimuli as directional or non-directional motion as shown in the bottom images.

the skin coordinate and environmental coordinate. Adaptation motion stimuli were presented on the index and middle finger with them crossed, where the middle to index finger motion resulted in rightward motion perception, while the index to middle finger motion resulted in leftward motion perception. After that, test motion stimuli were presented on the same two fingers with them uncrossed. If the MAE occurs according to the skin coordinate, the middle to index finger adaptation would induce an index to middle aftereffect; that is, rightward adaptation would induce a rightward aftereffect. If, on the other hand, the MAE occurs according to the environmental coordinate, rightward motion would induce a leftward aftereffect, which is the direction opposite to the skin-coordinate MAE.

We found that the direction of the tactile MAE was determined by the environmental coordinate (**Fig. 3**). When participants adapted to rightward motion (i.e., middle to index finger direction), they tended to report direction-ambiguous test stimuli as leftward motion; that is, they felt illusory motion with the middle to index finger direction after adapting to the motion with the middle to index finger direction. We also found that the MAE disappeared when the index and middle fingers were vertically aligned during adaptation, where the direction of adaptation motion was vertical, while that of the test motion was horizontal. These results suggest that direction of tactile motion is defined after skin input and posture information are integrated. In addition, we found no MAE when the adaptation motion was presented on the left hand and the test motion was presented on the right hand. This result suggests that the direction of tactile motion is likely to be defined at each side of the body, and that it involves tactile-specific processing rather than high-level super-modal motion processing. In summary, this study provides a novel behavioral method for accessing the tactile motion remapping from skin space into environmental/perceptual space.

4. Future research prospects

Our research group is trying to clarify the psychophysical mechanism for visual, auditory, and tactile inputs. Understanding the mechanism in our brain is also essential for developing user interfaces. For example, our group has developed a tactile navigation system called Buru-Navi (**Fig. 4**) [7]. Navigation through touch is a promising application for the future. It can provide direction information in an intuitive way as if one's hand was being pulled, and,

Fig. 4. Buru-Navi3 [7] force display device that generates a sensation of being pulled or pushed by exploiting the characteristics of human perception.

most importantly, the information can be obtained without preventing visual/auditory inputs.

At the same time, as mentioned above, direction in touch is non-unique, and it has many definitions. First, the direction is mapped on the skin coordinate and then remapped on the hand coordinate, arm coordinate, and body coordinate by taking body posture into account. Then the question is, to which coordinate should the navigation system show the direction when the device presents direction on the fingertip? Our results suggest that the direction at the hand/environmental coordinate is a better choice than that at the skin/finger coordinate since the brain calculates the direction on a fingertip after taking finger posture into account. Still, other questions remain such as whether the direction is calculated on the hand coordinate or body-centered coordinate and whether the same MAE can be observed (i.e., the same mechanism/theory is employed) when motion is presented with the palm-up posture. By gaining a more thorough understanding of information processing in the brain, we will contribute to developing unique, reliable, and user-friendly devices in the future.

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Standardization of Next-generation Wireless LAN IEEE 802.11ax

Shoko Shinohara, Junichi Iwatani, and Yasuhiko Inoue

Abstract

The gigabit-per-second class data transmission rate was achieved with the Institute of Electrical and Electronics Engineers (IEEE) 802.11ac standard. However, certain issues have emerged with wireless local area networks (LANs) because of their proliferation. The IEEE 802.11 committee is working to address this by standardizing a new wireless LAN system. The IEEE 802.11 Task Group ax, known as TGax, is considering various techniques to improve wireless LAN performance in dense deployment scenarios. This article introduces the target, use cases, and candidate technologies of the next-generation wireless LAN standard IEEE 802.11ax.

Keywords: wireless LAN, 802.11ax, high efficient

1. Introduction

Standards for wireless local area networks (LANs) are developed by the Institute of Electrical and Electronics Engineers (IEEE) 802.11 Working Group (IEEE 802.11 WG) of the IEEE 802 LAN/MAN (Mobile Area Network) Standards Committee. The recently published standard IEEE 802.11ac [1] enables very high throughput greater than 1 Gbit/s. Wireless LAN interfaces are being implemented in more and more products such as personal computers and mobile terminals such as smartphones, resulting in rapid growth of the market for Wi-Fi-enabled terminals, with over 12 billion cumulative shipments in 2015 [2].

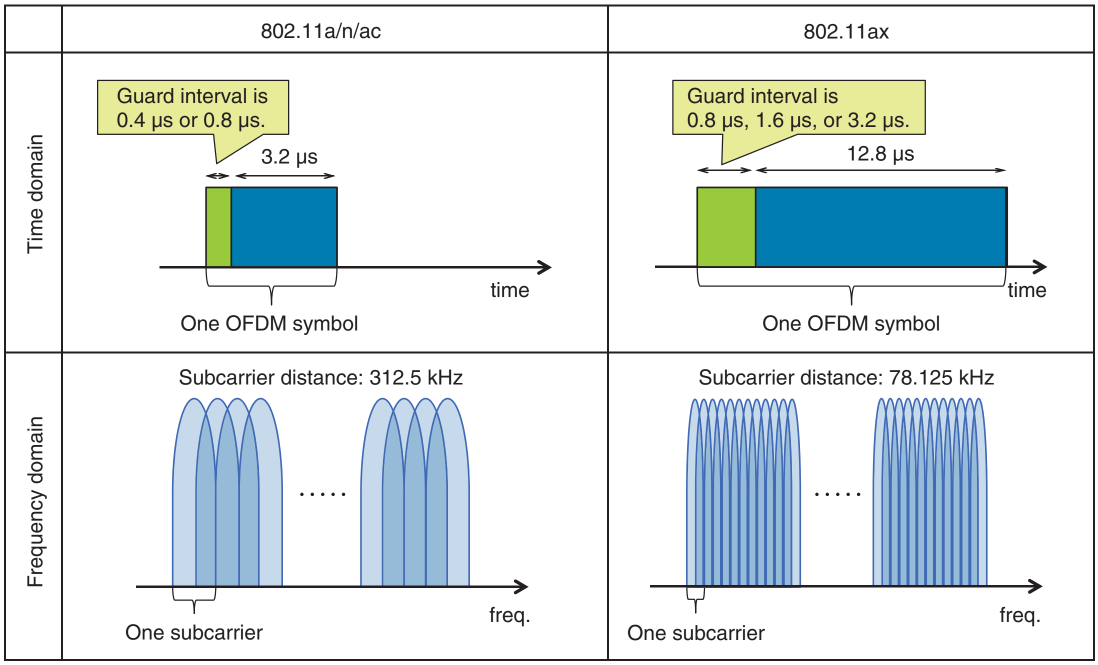
However, new problems have emerged with the proliferation of wireless LAN terminals. One problem is degradation of transmission efficiency, which occurs when many wireless LAN terminals interfere with each other. The reason for this is that wireless LAN devices acquire channel access opportunities in accordance with the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, which avoids simultaneous transmission on the same frequency resource. This means that the transmission opportunities of each terminal decrease in dense deployment scenarios.

Major Wi-Fi vendors and communication carriers including the NTT Group are working to overcome this and other challenges, and they have held discussions on the next-generation wireless LAN standard, which is intended to achieve high transmission efficiency even in dense wireless LAN environments. The IEEE 802.11 WG established a new task group that will work on the standardization of the next-generation wireless LAN 802.11ax standard in order to improve wireless LAN performance in dense environments [3, 4].

2. Scope of IEEE 802.11ax

Several technical requirements for the new wireless LAN standard were discussed before the creation of the Task Group ax (TGax) in the IEEE 802.11 WG. The conclusions of these discussions were summarized in a Project Authorization Request (PAR) [5] and in Criteria for Standards Development, which state the goal and the necessity of this standardization. The key points in the PAR are below, which states that the standard should:

- Modify both the IEEE 802.11 physical layers (PHY) and the IEEE 802.11 medium access control layer (MAC)
- Enable at least one mode of operation capable of



Guard interval: Time for providing immunity against inter-symbol interference.

Fig. 1. Four times longer OFDM symbol.

supporting at least four times improvement in the average throughput per station (terminal) measured at the MAC data service access point (SAP)*1 in dense deployment scenarios

- Maintain or improve the power efficiency per station
- Operate in frequency bands between 1 GHz and 6 GHz indoors and outdoors
- Enable backward compatibility and coexistence with legacy IEEE 802.11 devices operating in the same band

The primary objective of the 802.11ax standard is to achieve high efficiency in dense deployment scenarios. This differs from the main objective of 802.11ac, which is to increase the maximum MAC-SAP throughput. Consequently, the goal is not to achieve maximum throughput but to improve the average throughput per station.

IEEE 802.11ax is expected to significantly improve the communication quality and user experience in very populated areas such as train stations, airports, and stadiums. Furthermore, high transmission efficiency in dense deployment scenarios will result in an increase in the number of wireless LAN service users.

3. Techniques under consideration in 802.11 TGax

TGax is currently considering the use of various techniques in 802.11ax to improve spectrum efficiency:

- A signal format with high tolerance to delayed waves
- Multi-user transmission
- Spatial reuse of frequency resources

These are explained in the following subsections.

3.1 Signal format

In IEEE 802.11ax, the outdoor environment is viewed as an important scenario that has not been examined in detail. The main issue with the outdoor environment is a large delay spread of the radio signal. The delay spread tends to be larger in outdoor environments than in indoor environments, which causes serious degradation at the receiver. Therefore, in 802.11ax, the orthogonal frequency division multiplex (OFDM) symbol length will be extended by four times to combat the long delay spread in outdoor environments (**Fig. 1**). The expansion of the symbol

*1 MAC data SAP: Interface between MAC layer and upper layer.

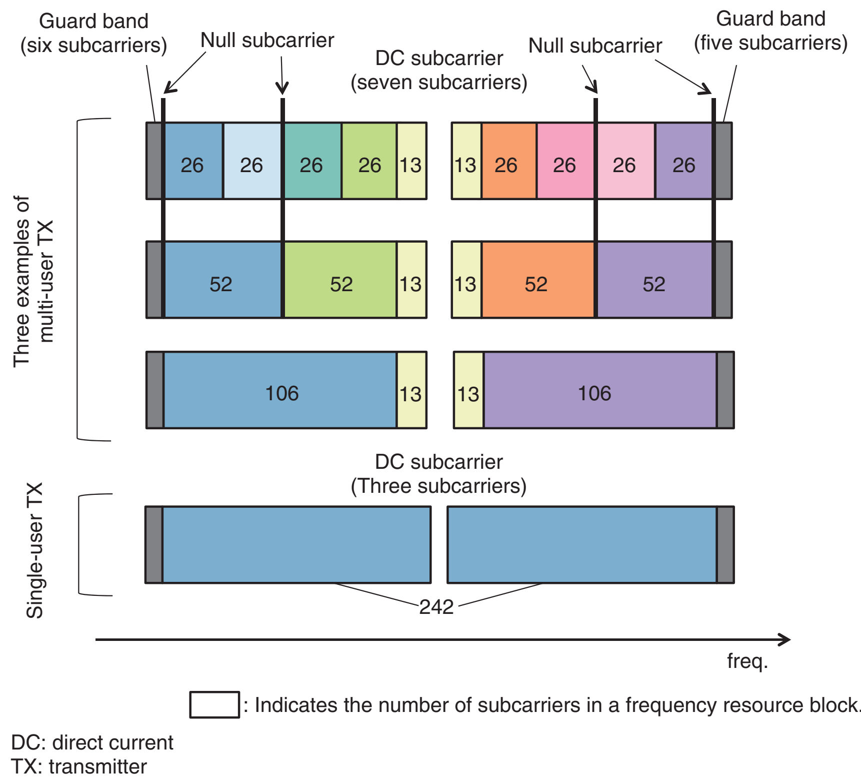


Fig. 2. Example of allocation of frequency resource block at 20 MHz.

length will also relax the timing requirement of uplink multi-user transmission. Moreover, it is expected to be more flexible when resources are allocated for OFDMA (OFDM access) transmission because the number of subcarriers*2 increases if the symbol length becomes longer.

3.2 Multi-user transmission

Multi-user transmission enables an access point (AP) to communicate with more than one client simultaneously. In the 802.11ac standard, downlink multi-user multiple input multiple output (MIMO) was introduced. The multi-user MIMO applies spatial multiplexing for transmission to more than one destination with one antenna or multiple antennas; in other words, it achieves higher spatial multiplexing gain and improves communication efficiency compared to single-user MIMO.

Further expansion of multiplexing and uplink/downlink directions are under consideration in discussions on the 802.11ax standard. To be more precise, (1) downlink OFDMA, (2) uplink OFDMA, and (3) uplink multi-user MIMO are under discussion. The downlink OFDMA has already been introduced in WiMAX (Worldwide Interoperability for Microwave Access) and LTE (Long Term Evolution), which use frequency multiplexing. The implementation to a module is easier than in multi-user MIMO, so it is expected to be used in more APs. In addition, several patterns of resource allocation have been proposed that will result in more efficient use of frequency resources, as depicted in **Fig. 2**. The uplink OFDMA and the uplink multi-user MIMO apply the multi-user transmission technique in the uplink direction. It is regarded as an effective technique to enhance the uplink transmission efficiency, particularly when there is a transmission acknowledgment for a multi-user downlink (**Fig. 3**). In order to achieve simultaneous transmissions from more than one station, a new control frame called a trigger frame has been discussed for timing synchronization in multi-user uplink transmissions.

3.3 Spatial reuse

In dense deployment scenarios, there will be several wireless LAN service areas on the same

*2 Subcarrier: Carrier wave multiplexed with OFDM.

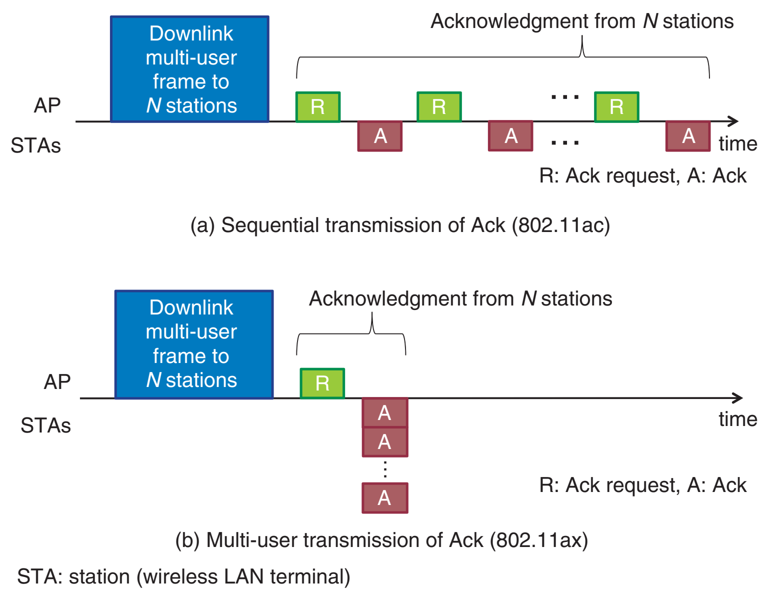


Fig. 3. Comparison of overhead needed for acknowledgment from more than one station.

frequency channel. In such cases, frequency resources are shared by those areas following the CSMA/CA protocol. To improve the spectrum efficiency of the service areas, control of the Clear Channel Assessment (CCA) threshold has been discussed as a way to enable frequency re-use at closer distances. The CCA threshold is used to determine the channel status—that is, whether it is IDLE or BUSY.

In the early days of wireless LAN, the density of wireless LAN terminals was not very high, and the CSMA/CA protocol with the existing CCA threshold worked very well. However, with the increasing popularity of wireless LANs, throughput degradation in dense environments has become much more serious due to inadequate transmission opportunities. In the 802.11ax standardization, controlling the CCA threshold is being considered as a solution for this problem. This technique makes it possible to set the CCA threshold higher than the conventional one when the channel has sufficient quality, which enables a new transmission to be started on top of an on-going transmission to improve the spatial spectral efficiency.

Of course, this technique is only possible when the existing transmission is happening in another wireless LAN area. If a wireless LAN terminal begins to transmit frames when another frame from the same cell is being transmitted, a packet collision would occur, and the transmission would not be received at the desired destination. Therefore, a method is needed to determine whether the receiving frame is from its own area or from another area, and thus, the use of an indicator in a PHY header is being discussed. When the receiving frame is determined to be from another area, the wireless LAN terminal will set the CCA threshold higher (**Fig. 4**), and channel contention will become more aggressive. Other conditions and the method of controlling the transmission power, which enables the CCA threshold to be controlled, are also under discussion. These promising techniques are expected to be useful to expand the system capacity.

4. Schedule of standardization

As of September 2016, technical discussions were continuing toward achieving draft version 1.0, scheduled for release in November 2016. Many companies including NTT and major Wi-Fi vendors are keeping up their efforts to complete the standardization of 802.11ax in order to release the official version after December 2018 (for details, refer to [3]) and to promote 802.11ax-compliant wireless LAN terminals leading up to 2020.

5. Summary

IEEE 802.11 TGax is considering techniques to

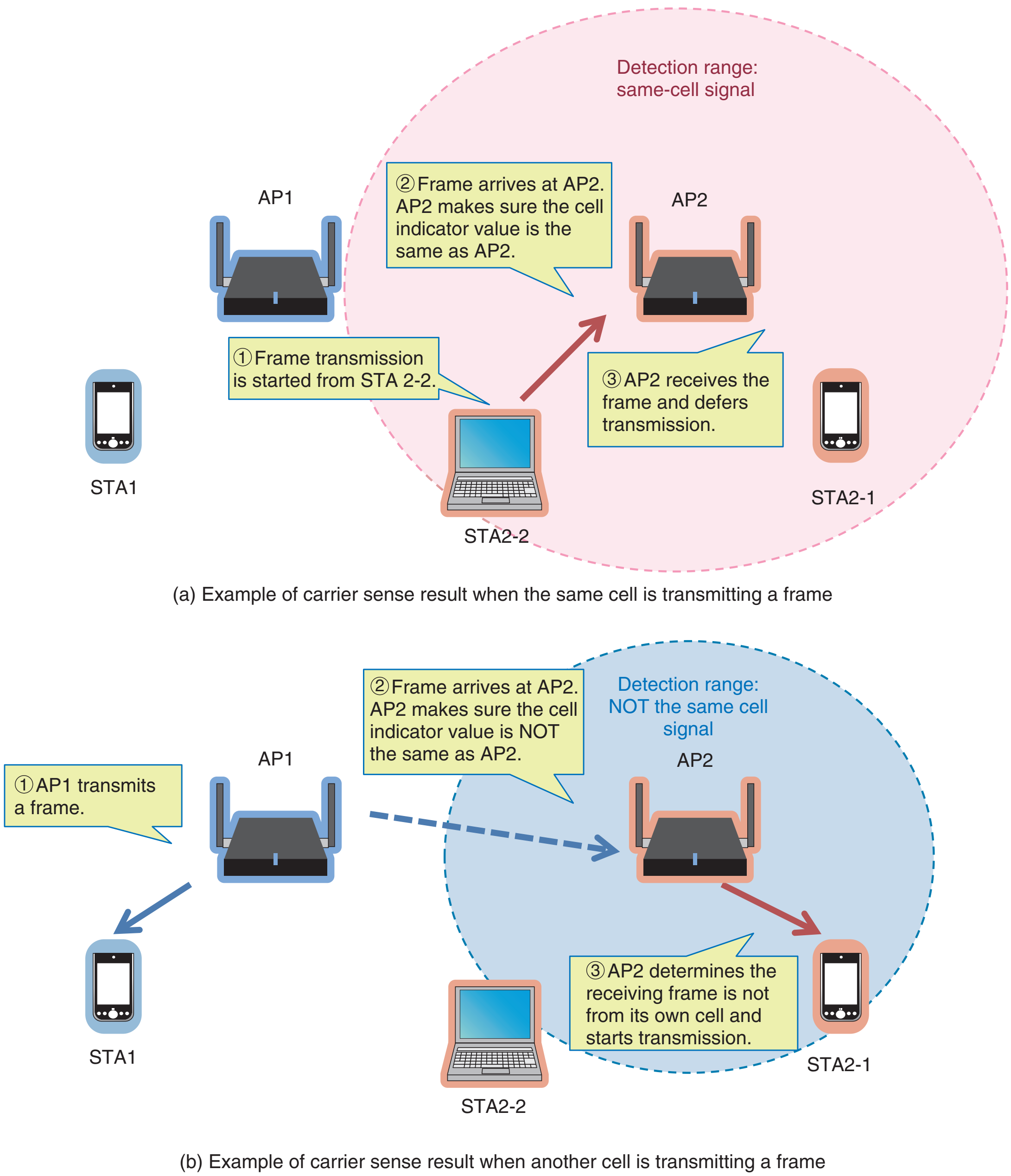


Fig. 4. Carrier sense based on the cell indicator.

ensure high throughput of wireless LAN transmissions even in dense environments. NTT is contributing to the development of the IEEE 802.11ax wireless LAN standard in order to resolve the performance degradation in high density environments and improve public wireless LAN services, including those in stadium environments.

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Achieving Tbit/s-level Transport Functions with White-box Switching on Virtual Networks—Driving NetroSphere with Network Architecture (MSF) that Maximizes General-purpose Equipment

1. Introduction

NTT has developed transport functions for carrier networks using white-box switches*1, which are general-purpose communications equipment, and demonstrated the possibility of configuring carrier-provided Tbit/s-level virtual networks using only general-purpose communications equipment. This has been achieved by using software that enables the use of Multi-Protocol Label Switching (MPLS) functions required for virtual networks, which were prepared as hardware for commercial white-box switches but could not be used. NTT has developed the software with completely open source technology so that many equipment vendors and carriers will be able to use this software in the future. As more equipment vendors begin to use this software, the white-box switch market that was once limited to the small-scale networks used in datacenters is expected to expand into the carrier network field. As well as having a much greater range of choices of network equipment, carriers will also have the ability to add functionality with network operating systems (network OS)*2 themselves. This will make network configuration more flexible and make it easier to provide even faster communication speeds and more customer-oriented services.

These achievements are a big step towards realizing the general-purpose, modularized networks aimed for with the Multi-Service Fabric (MSF), which is an elemental technology of NTT's NetroSphere concept established in 2015 [1, 2]. NTT plans to conduct ongoing studies and engage in experimental operation of its testing environment called NetroSphere PIT [3], which was developed to implement the NetroSphere concept, as well as to participate in wide-ranging collaborations as initiatives for achieving openness at an unprecedented level and expanding the use of this technology by improving its functionality.

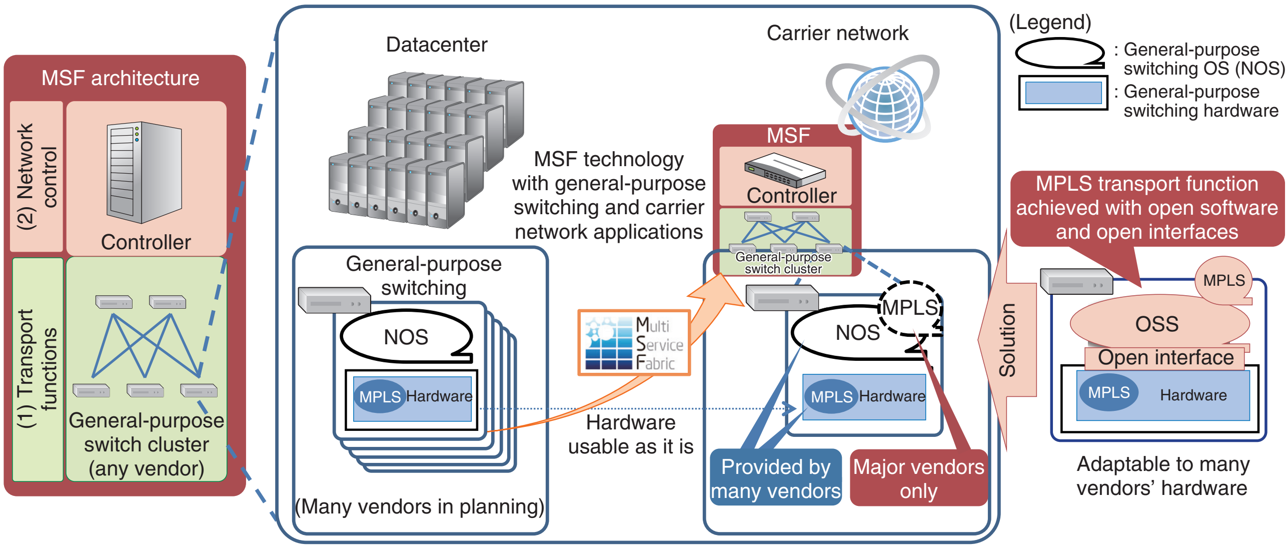
2. Background

Server performance and software technologies have improved in recent years, and with this, more and more virtual technologies have been adopted to economically achieve higher scalability and reliability, mainly in datacenters. The adaptation of these technologies for carrier networks by virtualizing computer and hardware resources has been gaining attention.

In line with the NetroSphere concept, NTT aims to provide both virtualization and fast, highly reliable, and even more diverse services to customers and service providers by driving commonization and modularization of network equipment. As part of these efforts, NTT is promoting its MSF initiatives to build

*1 White-box switch: General-purpose communications equipment that runs on equipment vendor hardware, for which software can be freely selected and developed.

*2 Network OS: Control software that runs internally in network equipment such as routers and switches.



NOS: network OS

Fig. 1. MSF transfer function problems and solutions.

networks using general-purpose equipment by using general-purpose products with simple functionality instead of specialized equipment with high functionality. Because network functions can be developed independently, MSF provides network architecture in which simplified hardware for transport functions and software for network control can be separated and redefined. This architecture is aimed at achieving transport functions that make maximum use of generic network switches (general-purpose switches) as well as flexible software functionality for network control.

3. Software that maximizes the use of white-box switching

MSF uses generic switches mainly used in datacenters and is aimed at achieving carrier network virtualization (to configure network slices), although this requires transport functions that use MPLS technologies. To date, however, MPLS transport functions have only been provided with software (network OS) by some router vendors, even though hardware is equipped with many general-purpose switches.

Hence, NTT has created a software product that is equivalent to a network OS. The product can be mounted on white-box switches to achieve MPLS transport functionality by making full use of hardware performance (**Fig. 1**).

4. Software overview and effects

The software uses two techniques to achieve MPLS transport. It generates optimal pathways by exchanging network path data with other MPLS routers, and it writes the generated paths to hardware through an interface that supports MPLS transport (**Fig. 2**). The software functions are configured using only commercially available open source technologies such as open source software (OSS), so white-boxing is possible even in internal software configurations. At the same time, using architecture that maximizes hardware performance enables high-capacity, carrier-grade transport with white-box switching (1 Tbit/s/tens of thousands of paths).

These achievements mean that it is possible to apply general-purpose switches to carrier networks, and consequently, equipment vendors will be able to pioneer new markets (for general-purpose switches for carrier networks), which should bring down prices for general-purpose switches as well as lead to additional functionality through competition among vendors. Moreover, carriers will have a greater selection of equipment with which to build networks, and they will be able to modify network OS software by themselves.

These developments are driving the NetroSphere concept and MSF objectives of network commonization and modularization and will make it easier to

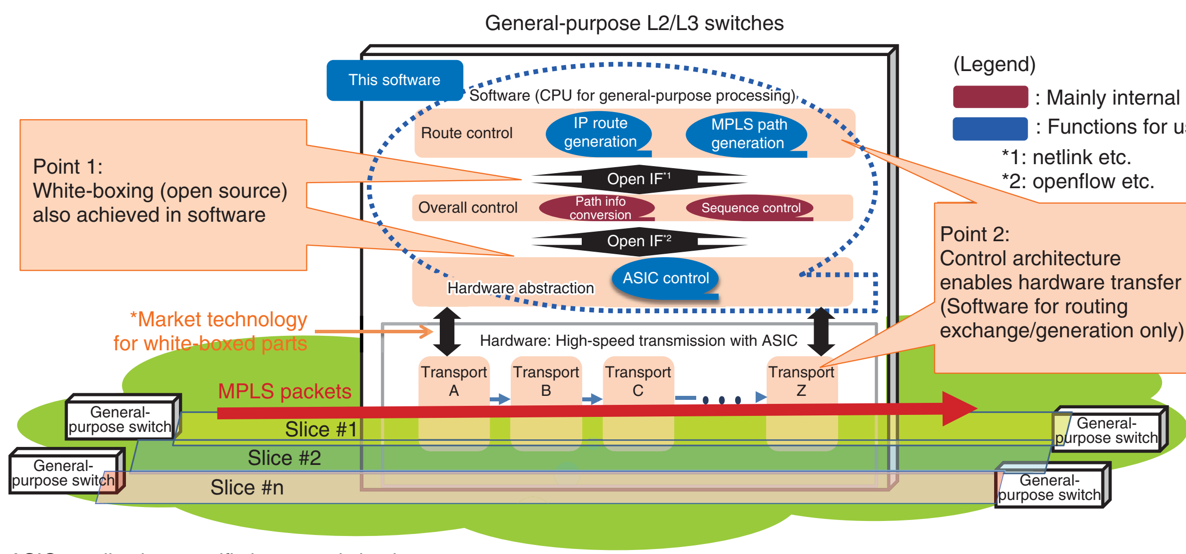


Fig. 2. Technical overview (software for white-box switches).

meet customer requirements with even faster communication speeds.

5. Future outlook

Beginning with NetroSpherePIT, NTT plans to carry out studies on experimental operations and further expansion of functionality in order to establish this technology, and to engage in even greater levels of openness by forming wide-ranging partnerships with various organizations.

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External Awards

Outstanding Presentation Award
Winner: Ryunosuke Sudo, Kyushu University; Daisuke Satoh, NTT Network Technology Laboratories; Yuji Takano, Doshisha University; Takemi Mochida, NTT Communication Science Laboratories
Date: June 16, 2016
Organization: The Japanese Psychological Association

For "Examination of the Measures and Subjective Stress of Calling Party during Disaster."
Published as: R. Sudo, D. Satoh, Y. Takano, and T. Mochida, "Examination of the Measures and Subjective Stress of Calling Party during Disaster," The 79th Annual Convention of the Japanese Psychological Association, 3EV-029, Nagoya, Japan, Sept. 2015.

Information Security Leadership Achievements (Senior Information Security Professional category)
Winner: Hisashi Kasahara, NTT Electronics
Date: July 26, 2016
Organization: International Information Systems Security Certification Consortium $(ISC)^2$

For his contributions to the development and education of information security professionals for more than ten years as a leader in the Asia-Pacific region.

CSS2016 Student Paper Award
Winner: Yumehisa Haga, Waseda University; Yuta Takata and Mitsuaki Akiyama, NTT Secure Platform Laboratories; Tatsuya Mori, Waseda University
Date: October 12, 2016
Organization: Information Processing Society of Japan (IPSJ) Computer Security Symposium (CSS) 2016 program committee

For "An Implementation of Web Tracking Detection System and an Investigation of Third-party Tracking Sites."
Published as: Y. Haga, Y. Takata, M. Akiyama, and T. Mori, "An Implementation of Web Tracking Detection System and an Investigation of Third-party Tracking Sites," CSS2016, 3B3-1, Akita, Japan, Oct. 2016.

CSS2016 Paper Award
Winner: Naoto Kiribuchi, Dai Ikarashi, Gembu Morohashi, and Koki Hamada, NTT Secure Platform Laboratories
Date: October 12, 2016
Organization: IPSJ Computer Security Symposium (CSS) 2016 program committee

For "An Efficient Equi-Join Algorithm for Secure Computation and Its Implementation Toward Secure Comprehensive Analyses of Users' Attribute and History Information."
Published as: N. Kiribuchi, D. Ikarashi, G. Morohashi, and K. Hamada, "An Efficient Equi-Join Algorithm for Secure Computation and Its Implementation Toward Secure Comprehensive Analyses of Users' Attribute and History Information," CSS2016, 3A3-4, Akita, Japan, Oct. 2016.

MWS2016 Best Paper Award
Winner: Bo Sun, Waseda University; Mitsuaki Akiyama, NTT Secure Platform Laboratories; Tatsuya Mori, Waseda University
Date: October 12, 2016
Organization: IPSJ Anti Malware Engineering Workshop (MWS) 2016 program committee

For "Toward Automatically Detecting Promotional Attacks in Mobile App Store."
Published as: B. Sun, M. Akiyama, and T. Mori, "Toward Automatically Detecting Promotional Attacks in Mobile App Store," MWS2016, 3F2-4, Akita, Japan, Oct. 2016.

Specially Selected Paper
Winner: Hiroaki Kikuchi, Meiji University; Katsumi Takahashi, NTT Secure Platform Laboratories
Date: October 12, 2016
Organization: IPSJ

For "Zipf Distribution Model for Quantifying Risk of Re-identification from Trajectory Data."
Published as: H. Kikuchi and K. Takahashi, "Zipf Distribution Model for Quantifying Risk of Re-identification from Trajectory Data," Journal of Information Processing, Vol. 24, No. 5, pp. 816–823, 2016.

Best Paper Award
Winner: Motoharu Sasaki, Minoru Inomata, Wataru Yamada, Naoki Kita, Takeshi Onizawa, Masashi Nakatsugawa, NTT Access Network Service Systems Laboratories; Koshiro Kitao and Tetsuro Imai, NTT DOCOMO
Date: October 27, 2016
Organization: ISAP2016 (International Symposium on Antennas and Propagation)

For "Path Loss Characteristics between Different Floors from 0.8 to 37 GHz in Indoor Office Environments."
Published as: M. Sasaki, M. Inomata, W. Yamada, N. Kita, T. Onizawa, M. Nakatsugawa, K. Kitao, and T. Imai, "Path Loss Characteristics between Different Floors from 0.8 to 37 GHz in Indoor Office Environments," ISAP2016, Okinawa, Japan, Oct. 2016.

Early Career Award
Winner: Tetsuhiko Teshima, Hiroshi Nakashima, Yuko Ueno, Satoshi Sasaki, and Shingo Tsukada, NTT Basic Research Laboratories
Date: November 10, 2016
Organization: The Chemical Society of Japan, Division of Colloid and Surface Chemistry

For "Self-folded Thin Polymer Film for Encapsulation and Manipulation of Cells."
Published as: T. Teshima, H. Nakashima, Y. Ueno, S. Sasaki, and S. Tsukada, "Self-folded Thin Polymer Film for Encapsulation and Manipulation of Cells," The 67th Divisional Meeting on Colloid and Interface Chemistry International Symposium, 3B05, Asahikawa, Hokkaido, Japan, Sept. 2016.

Best Industry Paper Award
Winner: Jun Hagiwara, NTT DATA; Shinobu Saito, NTT Software Innovation Center
Date: November 11, 2016
Organization: The Third Asia Pacific Requirements Engineering Symposium (APRES 2016)

For "MOYA: Model-oriented Methodology for Your Awareness." **Published as:** J. Hagiwara and S. Saito, "MOYA: Model-oriented Methodology for Your Awareness," Proc. of APRES 2016, CCIS 671, pp. 68–78, Nagoya, Japan, Nov. 2016.

Papers Published in Technical Journals and Conference Proceedings

Extracting Current Waveforms of Appliances from Mixed Current Waveform of Their Current Waveforms and Unidentified Current Waveforms

F. Ishiyama, H. Inoue, and Y. Suzuki

Proc. of 2016 IEEE 12th International Colloquium on Signal Processing & its Applications (CSPA2016), pp. 16–21, Melaka, Malaysia, March 2016.

We propose a method of extracting current waveforms of appliances from the current waveform, which is a mixture of their current waveforms and unidentified current waveforms. The purpose of the method is to monitor the load of individual appliances by analyzing the current waveform on a power distribution board. Since the mixed current waveform contains unidentified current waveforms, a special method is required. Therefore, we propose to apply our method, called the "inscribed fitting method" with an asymmetric evaluation function, for the extraction. We apply our method to the mixed current waveforms of appliances, showing that we can extract the current waveforms of appliances from the mixed current waveforms which contain unidentified current waveforms.

Ancilla-driven Instantaneous Quantum Polynomial Time Circuit for Quantum Supremacy

Y. Takeuchi and Y. Takahashi

arXiv:1611.00510 [quant-ph], November 2016.

Instantaneous quantum polynomial time (IQP) is a model of (probably) non-universal quantum computation. Since it has been proven that IQP circuits are unlikely to be simulated classically up to a multiplicative error and an error in l_1 norm, IQP is considered one of the promising classes that demonstrate quantum supremacy. Although IQP circuits can be realized more easily than a universal quantum computer, demonstrating quantum supremacy is still difficult. It is therefore desired to find subclasses of IQP that are easy to implement. In this paper, by imposing some restrictions on IQP, we propose ancilla-driven IQP (ADIQP) as the subclass of commuting quantum computation suitable for many experimental settings. We show that even though ADIQP circuits are strictly weaker than IQP circuits in a sense, they are also hard to simulate classically up to a multiplicative error and an error in l_1 norm. Moreover, the properties of ADIQP make it easy to investigate the verifiability of ADIQP circuits and the difficulties in realizing ADIQP circuits.