# NTT Technical Review

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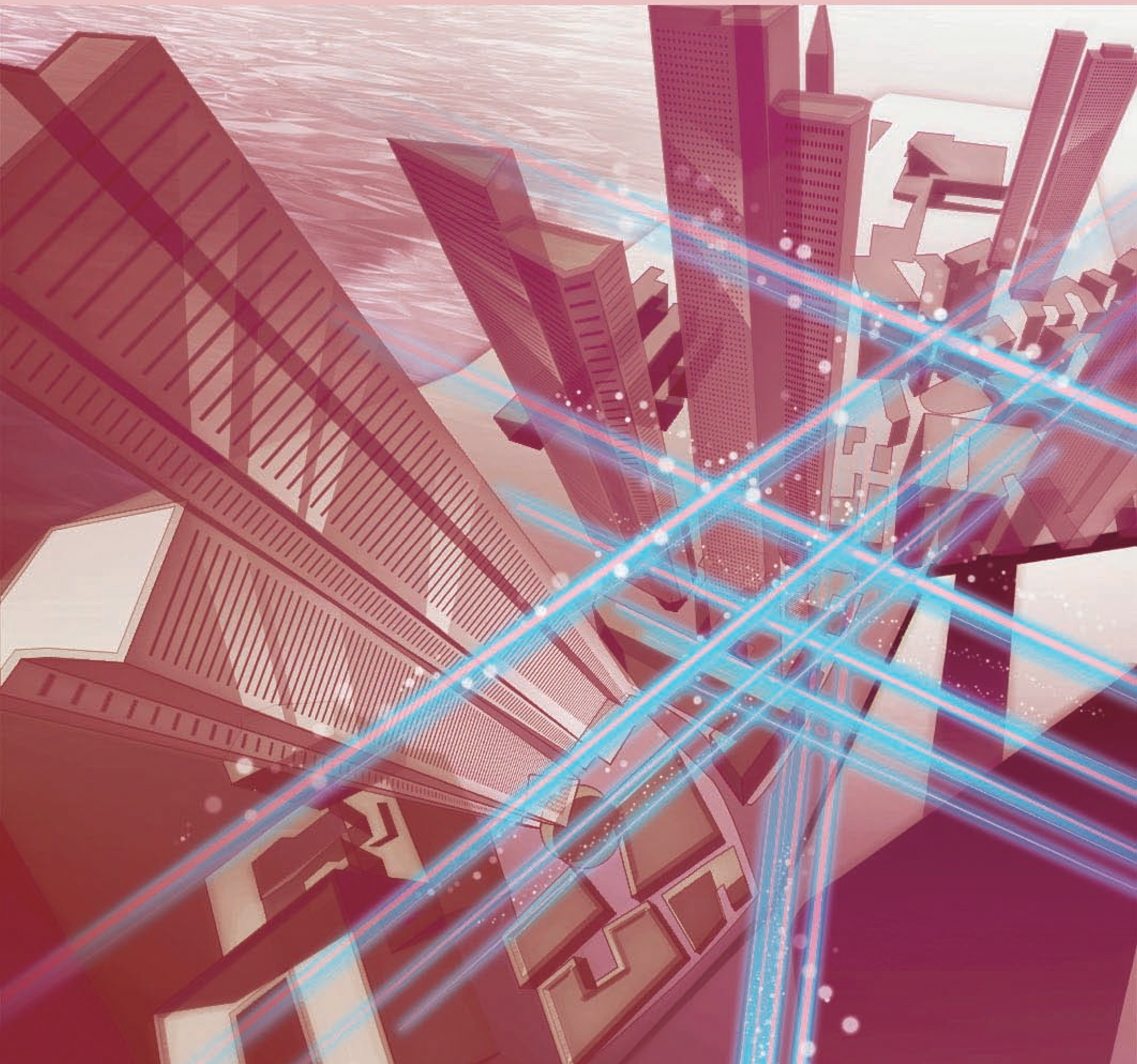

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# NTT Technical Review

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# Creating New Value with a Spirit of One for All, All for One—Using Human Sensitivities to Popularize Services

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**Overview**

The NTT Group has taken up the challenge of self-transformation toward growth in profits as declared in its Medium-Term Management Strategy "Towards the Next Stage 2.0." There are high expectations of the NTT Group for technological development and social contributions in fields of great global interest such as artificial intelligence, Internet of Things, and cybersecurity. At the dawn of a new year, we asked Senior Executive Vice President Hiromichi Shinohara to tell us about NTT Group plans for 2016 and specific initiatives for creating new value.

*Keywords: R&D, artificial intelligence, cybersecurity*

## 2015: NTT Group makes a big turn from a main player to a catalyst

*—Mr. Shinohara, what kind of results were obtained last year under the new Medium-Term Management Strategy?*

To begin with, the entire NTT Group has endeavored to change its mindset. We have abandoned our sense of being a "main player" and have put ourselves on the path to becoming a "catalyst." The NTT Group announced this change in direction in its Medium-Term Management Strategy "Towards the Next Stage 2.0" presented in May 2015. There are two main pillars to this strategy. One is self-transformation with the aim of becoming a "value partner" and increasing profits. The other is further promotion of the business-to-business-to-X (B2B2X) model and the opening up of new business fields and markets.

One example of self-transformation is the launch of the Hikari Collaboration Model by NTT EAST and NTT WEST. This model involves wholesaling of optical-fiber access services and has enabled us to start providing new value to our customers in cooperation with many partners other than telecom carriers. More developments are needed here, but we have gotten off to a good start.

In tandem with these efforts, NTT research and technology development has been focused on improving cost efficiencies by simplifying the network and preparing technologies essential to new services in the form of standardized "engines." In addition, we pursued collaboration and open innovation with group companies and various partners. One example is the functional fabric called "hitoe" that can provide biomedical information simply by wearing it. In

December 2014, NTT DOCOMO launched a fitness service using hitoe called "Runtastic for docomo," and not to be outdone, NTT Communications began tests of a safety management system in which staff of major corporations such as the construction firm Obayashi and Japan Airlines are asked to wear hitoe material in the field. NTT DATA, moreover, is working on using hitoe as a real-time tool for measuring the condition of drivers in IndyCar racing in the United States, and studies are also underway on the use of hitoe for measuring the heart rate and myoelectric signals of pilots in the jet fighter test environment of Japan's Ministry of Defense. Indeed, the possible applications of hitoe have expanded greatly this last year.

As a result of these activities, I think I can safely say that this past year marked a major turn for the entire NTT Group in a new direction based on the keyword "collaboration."

*—A huge amount of energy would be needed to move such a massive organization as the NTT Group. How do you keep everyone and everything in step?*

When determining to move in the direction of new value, I think there are two ways to go about it. One is to get everyone moving after giving instructions on what needs to be done, and the other is to get everyone moving by sharing an awareness of the problem and an understanding of the objective. Sometimes I feel that giving instructions is important, but I also think it's important that I get everyone to empathize with the NTT Group objectives and way of thinking and to think about the best way of dealing with problems that we will have to confront from here on. For example, I have begun summoning those in charge of technology development at the various group companies to share each other's research and development (R&D) plans and to discuss what should be developed in common. Here, with an eye to creating new services and accelerating the generation of profits while eliminating waste in technology development, we looked for technologies that could be shared by group companies. These efforts have been producing results. I believe that experiencing such a string of successes leads to ongoing, self-motivated activities within the NTT Group.

## Linking people and technology to create new value

*—How do you plan to expand upon last year's efforts?*

One way is to make an all-out effort to create new value to drive the growth of the NTT Group. Here, I would like to accelerate the development of a B2B2X model. Moreover, from the viewpoint of R&D, stepping up the standardization of engines (technologies) is important. Last year, for example, the NTT Group announced a variety of interactive, talking robots typified by one named "Sota." These robots incorporate advanced technologies for natural-language processing and other functions, but up to now, they have been independently developed and supported. This approach, however, incurs unnecessary expenses and slows down the development process, so from here on, I would like to further promote the standardization of technologies.

Another way is to accelerate "hybrid development." Up to now, we have been creating better services by promoting joint development with NTT Group companies, but this year, I would like to accelerate the speed of providing services to the market from the research stage. To this end, I will promote joint activities from early on and target market needs for development. I would also like to envision those parts of a service that customers may not be aware of in the present and incorporate those parts in development projects. Thus, in addition to simply doing something because we are asked to do so by customers, I would like to improve our competence at predicting future needs and responding accordingly. We need to look into the future and move forward in the present. To begin with, I would like all of us to develop those ways of thinking!

Regarding the network business, our goal was conventionally to achieve higher levels of quality. However, considering today's customer needs, the network must be simplified, and the cost efficiency of operations and maintenance must be improved to increase the profits of the entire NTT Group. To this end, NTT announced the future network vision "NetroSphere" in February last year, and since then, we have been steadily forming business relationships, so I would like to make this year one for implementing this concept in tangible ways.

I would also like to channel the results of development projects done at NTT Innovation Institute, Inc. (NTT $I^3$) to specific market needs in order to generate profits in global cloud services. To push this along, I would like to deepen the ties between NTT $I^3$ and NTT laboratories on the Japan side.

*—How do you approach the fields of AI, IoT, and cybersecurity, today's top keywords?*

Supercomputer performance, which at one time was available to only a few people, is today achieved in smartphones, which many people now take for granted as a tool they can use in the palm of their hand. Advances in technology are truly amazing, but they do not always translate into better lives for people. As for artificial intelligence (AI), it has not yet reached a level that can truly transform society. In addition to making society more efficient and convenient for people, I would like to see AI play a role in achieving a prosperous society by helping to make the lives of many people enriching and fulfilling in the true sense of the words. Details on our AI initiatives will be announced at the NTT R&D Forum in February 2016, but we can broadly divide them into four areas. These are Agent AI that does things for people, Ambient AI based on massive amounts of data in relation to Internet of Things (IoT), Network AI that links to networks, and Heart-Touching AI that interacts with people in a human-friendly way. Going forward, we will continue to pursue ways in which AI can be beneficial for our lives.

Next, as for IoT, there will be various requirements depending on the application field. This year, I would like to produce concrete examples of IoT applications in collaboration with partners. Data will become of prime importance in this endeavor. However, data involves not only machines but also individuals and their personal attributes, so care must be taken in how to obtain data from people, in how to safely use and combine that data, and in how to otherwise apply that data in an appropriate manner. In addition, it's not just technology that matters here but also the creation of new value from collected data. I therefore believe that gathering data in a divided "silo-type" manner is not enough, and that it will become increasingly important to coordinate different types of data in some way.

In terms of cybersecurity, we plan to build up our training program for security personnel in the NTT Group, and we aim to establish a security force on the scale of about 10,000 people within Japan by 2020. Last year, we completed our first round of certifications for security qualifications and we will continue to develop ourselves in this area. However, when thinking ahead to 2020, it's not only telecom carriers but all operators involved with critical infrastructure that must address the need for robust security measures. Today, just about everything including manufacturing plants and rail transport is connected to the network, so security measures constitute an investment for future growth and a major management issue. All companies and enterprises must identify what needs to be protected within their operations and must examine their ability to ensure security. With this in mind, NTT established the "Cross-Sector Cybersecurity Forum" in June of last year to contribute to the training of security personnel in Japan and to promote information sharing. This forum has so far enabled more than 40 participating companies to introduce their efforts in developing security personnel, present training case studies, exchange ideas and opinions, and talk about each other's state of security. In this way, each company can reexamine the problems they are facing and consider appropriate solutions. Even companies that had thought they were doing okay when it comes to security have come away from such gatherings with a heightened sense of danger and a resolution to enhance their security measures. This year, I would like to promote the sharing of security-related information with global telecom carriers and to deepen our interaction with them.

Finally, as an example of activities toward 2020, we gave proof of concept (PoC) presentations on some of our R&D results at last year's NTT R&D Forum. At this year's forum, I would like to connect PoC to actual applications and specific ways of achieving them together with attendees. To this end, the ability to convey things to people with a richer level of expression will become necessary, so I think that collaboration with people who have highly developed senses, have extensive experience, and are sensitive in nature will become important from here on. In particular, when introducing foreigners to Japanese culture, we must keep in mind that "every man knows his own business best." At NTT, technology is our business, but there are people that are considerably more knowledgeable, experienced, and emotionally equipped to convey the diverse aspects of culture. Certainly a richer level of expression can be achieved by tapping the abilities of professionals and people directly involved with culture.

## Importance of resolution and effort in popularizing a new development

*—Mr. Shinohara, can you leave us with a message for all employees in the NTT Group?*

I would be happy to. This is the year that the true worth of collaboration will be put to the test. Collaboration is a summation of individual strengths. It is a natural tendency to do what we are capable of doing and to rely on others to do what we cannot. We should have the courage to refrain from doing some things even if we feel we can do them on our own. There are also times when we need to discard some things in our quest to create something strong and lasting. This is a matter of self-discipline. To this end, I would like us to build relationships with partners in which conversations can be held on an equal footing. This may sound easy, but it's actually difficult; an equitable relationship is inherently unstable. But I would like everyone to keep this goal in mind.

In addition, we need to remember that developing something new must be accompanied with efforts to spread and popularize that new technology or service. Here, the resolution and effort required to popularize something new is different from that needed to develop it. Leaving one's mark on society is truly a good feeling. I would like to ask each and every employee to think about the best way of popularizing a service that we have developed that has something to offer society. In a sense, the word "universal" is similar to "popular," but giving an existing thing value to make it universal is different from discovering something that is universal in a new way. Wouldn't this challenge of searching for universality be interesting?

Considering that we may spend about 30 years in the workplace, it is impossible to keep up a winning streak throughout that time. There are times when we inevitably have to lose. Instead of being focused on winning or losing, I would like everyone to think hard on what the company and society at large should be like.

If we attempted 100 development projects and failed 90, instead of dwelling on the 90 failures, we can say that this is a process that gave birth to 10 successes. Moreover, from the viewpoint of the entire NTT Group, it can be said that a failure in one division sometimes leads to a success in another. Failure is evidence of great effort. Let's take up the challenges of R&D without fear.

By the way, rugby, which is famous for its "one for all, all for one" spirit, is growing in popularity thanks to the success of the Japanese national team in the Rugby World Cup last year. I believe that people felt the power of a team in addition to the power of individual players. Let's think of the entire NTT Group as a team and let's venture into the new era together.

**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.

# Making Photonic Devices Dramatically Larger in Scale and Lower in Price


***Shinji Matsuo***
***Senior Distinguished Researcher, NTT Device Technology Laboratories***



## Overview

Shinji Matsuo, Senior Distinguished Researcher at NTT Device Technology Laboratories, continues his challenging work on achieving optoelectronic integrated circuits on silicon substrates and making them into economical and low-power devices—key issues in the worldwide information technology industry. He leads a group dealing with a unique form of research, so we asked him to give us some background on the inception of this groundbreaking technology. We also asked him to describe remaining issues and to comment on his role as a researcher.


*Keywords: photonic device, optoelectronic integrated circuit, laser on Si*

## Laser on Si: a long-standing challenge

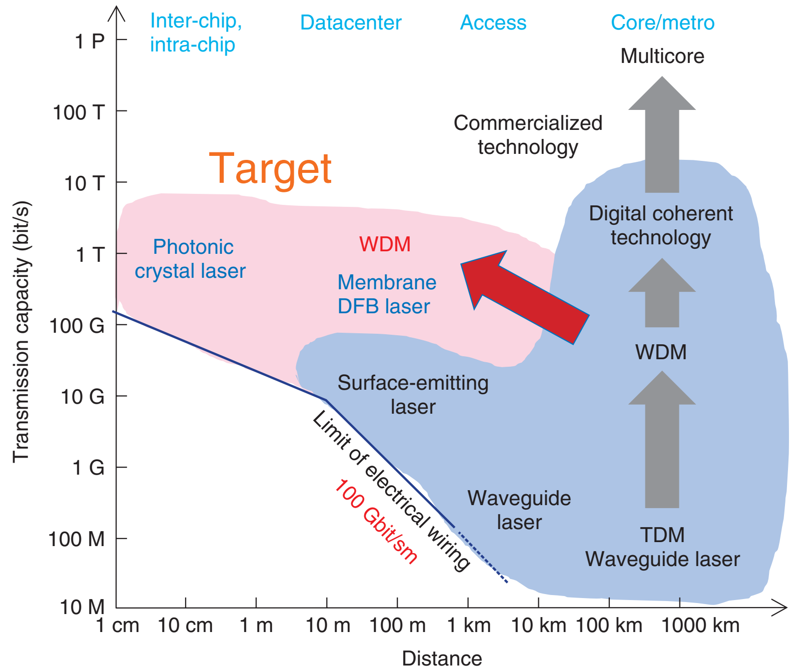
*—Dr. Matsuo, please tell us about your current research efforts.*

In Japan, mobile data traffic is predicted to grow by about 1000 times the 2010 level by 2025. At datacenters too, traffic volumes are growing at an amazing rate. Facility investment is needed to deal with this jump in traffic, but passing on this cost to customers through usage fees must be prevented. The amount of power used by datacenters is also a key issue. In the United States, for example, it accounts for a substantial percentage of all power consumed in the country. In this regard, 70% of datacenter traffic is made up of communications within the datacenter, so "economical" and "low-power" are becoming important keywords when talking about short-range optical communications in datacenters.

In photonic devices too—my field of research—there is considerable activity in solving these problems in optical communications.

In the field of electronic devices such as silicon-based complementary metal-oxide semiconductors (CMOS), innovation in integration technology has enabled the number of transistors in an integrated circuit to increase by 1 million times over a 40-year period in accordance with Moore's law while minimizing cost increases.

In the field of photonic devices, however, the modularization of individual components such as lasers, light-receiving elements, and isolators is still just a concept. To achieve photonic devices with large-scale integration and low cost on a level equivalent to that




DFB: distributed feedback
TDM: time division multiplexing
WDM: wavelength division multiplexing

Fig. 1. Expanded application of optical communications technology.

of electronic devices, we need to develop optoelectronic integrated circuits on a silicon platform and establish silicon photonics technology that can increase integration density by 100–1000 times that of current levels. To this end, we have been looking into the use of compound semiconductors such as indium phosphide (InP) and gallium arsenide (GaAs) in the field of optoelectronic integration in a scheme similar to the use of silicon. If this could be achieved and if semiconductor lasers could be manufactured by a mechanism similar to that of a silicon fab*, the cost per bit could be decreased by 1/1000 in 20 years by what we could call an optical version of Moore's law (**Figs. 1–3**).

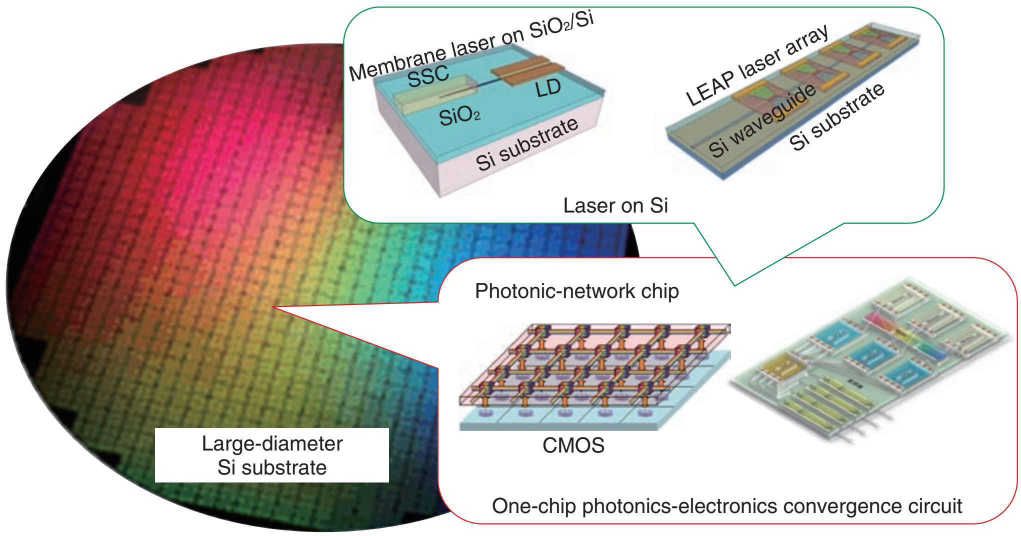
*—Has this research progressed smoothly?*

There are two main technical issues in achieving laser on Si (silicon). These have presented a challenge to me ever since I entered NTT laboratories about 30 years ago.

The first is lattice misalignment. The atomic size of silicon (group IV in the periodic table) and that of compound semiconductors such as InP and GaAs (group III-V) are different, so growing a compound semiconductor directly on silicon is extremely difficult. To resolve this issue, we developed technology for preparing silicon and a compound semiconductor separately and then joining them directly at the atomic level.

The other issue is different thermal expansion coefficients. The temperature in the laser fabrication process increases from room temperature to 600°C, but the thermal expansion coefficients of silicon and InP differ greatly. As a result, the different amount of thermal expansion in those materials as the process temperature changes can cause strain and stress to occur, which can lead to defects in the crystal and a significant drop in device characteristics. In light of this, conventional semiconductor lasers have been fabricated with a thickness of several micrometers. However, by making use of membrane lateral injection fabrication technology developed in conjunction

* Silicon fab: A plant for fabricating silicon CMOS circuits. Many units of very expensive manufacturing equipment are needed to fabricate ultra-fine CMOS devices, so having more than one company use the same plant instead of each company having its own can significantly lower manufacturing costs.




LD: laser diode
LEAP: lambda-scale embedded active-region photonic-crystal
Si: silicon
$SiO_2$: silicon dioxide

Fig. 2. Large-scale optoelectronic integrated circuits using “laser on Si” technology.

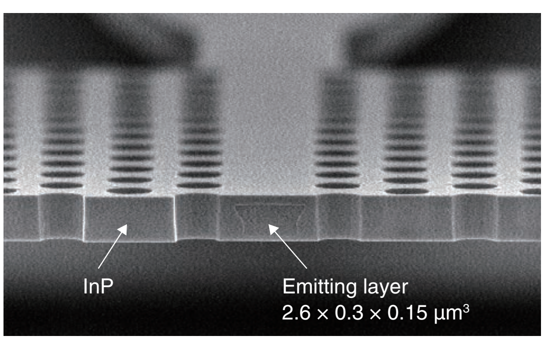



Fig. 3. Cross section of LEAP laser.

with a LEAP (lambda-scale embedded active-region photonic-crystal) laser that we successfully developed in 2013, we achieved a breakthrough in laser membrane thickness, reducing it to about 1/10 that of the conventional level.

I believe that this achievement was a direct result of the world-class expertise of NTT laboratories in epitaxial growth technology and optical semiconductor processing technology (**Fig. 4**).

*—What issues lie ahead?*

I would like to try fabricating an actual large-scale photonic integrated circuit with lasers using a silicon fab. Of course, the use of a silicon fab means that this would not be something that NTT could accomplish on its own, so we would need to do this together with many other parties. To this end, we will promote discussions at international conferences that up to now have not been directly related to lasers and actively pursue joint research with outside parties. We will also work to persuade industry leaders, university professors, etc., to support the direction of our research.

*—This research has been attracting attention in many countries. What has been the response?*

I have had many opportunities to present my research in the form of invited lectures in Europe, the United States, China, and other countries to people involved in similar research, so I feel that interest is growing in our technology.

I have also noticed a growing interest from other fields in our technology for fabricating lasers on silicon. The questions that I receive have likewise been changing from general impressions such as “very unique characteristics” to specific inquiries such as “Can this really be used?” and “Can this be incorporated in the silicon fab mechanism?” I think this is because of growing expectations for actual application

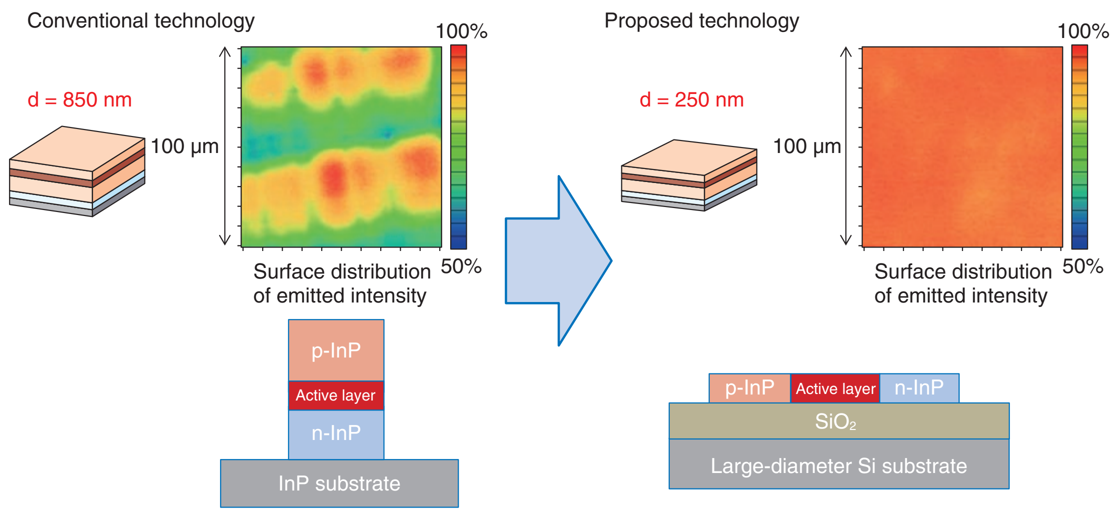



Fig. 4. Core technology for achieving laser on Si.

and commercialization of this technology.

Thus, while I think that this is a great accomplishment from a technical point of view, there are still issues that need to be resolved in terms of reliability and cost efficiency before we reach a practical stage. This research is progressing steadily, but when considering the objectives to be attained, it is still in its second stage.

## "You evaluate yourself"—surrounding yourself with brilliant people and recognizing your strong points

*—In what sort of environment and from what mindset did these epoch-making research achievements originate?*

We have abundant human resources at NTT laboratories, with specialists in a variety of fields, and I enjoy having the opportunity to chat with such bright people over drinks whenever possible. Our discussions at such sit-downs are lively, and new projects may get off the ground with declarations such as, "If that's the case, let's work together and give it a try!" Senior Distinguished Researcher Masaya Notomi, known for his research in photonic crystals, is one such colleague.

In the actual research process, ideas may come to such specialists in a variety of ways. Because such a distinguished group of people have been purposely brought together, it's imperative that ways be found for making the most of their amazing abilities in my research with the ultimate aim of producing results.

It was once said to me: "You know best as to who has the technology that we need." On hearing that, I suddenly realized one of my strong points—knowing where to find certain technologies. I also keep in mind that "you evaluate yourself," and that I should be careful not to be swayed by the judgments of others.

This mindset actually began when I succeeded for the first time in achieving laser oscillation on a silicon substrate. I immediately tried to announce this technology in a post-deadline paper at the Optical Fiber Communication Conference, but the paper was not chosen. However, I persevered in announcing my results in later papers and elsewhere, and I finally began to receive some recognition. In other words, the position, background, viewpoint, etc., of an evaluator can influence the evaluation in question.

The same holds true for evaluations within the company. The staff of a company is not solely composed of specialists, so it cannot be said that those evaluations are always correct. For me, in all honesty, you live or die by whether a device works or fails rather than by the opinions of others. I take great pleasure in research. By the way, to tell you something about my personal life, I put a lot of effort in tending the garden at home. Similar to research, flowers may not bloom as expected, and weeds that spring up daily must be constantly pulled. However, unlike research, results in gardening can be obtained relatively quickly, and most people will find the results of your time and effort and care as something beautiful. This is why gardening is relaxing and enjoyable for me. In the case of research, it's not all praise; most feedback is negative in nature.

*—As an active researcher, what do you think is important to produce results?*

I believe that a change in perspective can be very helpful. It is also important to have motivation and to merge information.

In 1997, exactly ten years after entering NTT, I was assigned to the NTT laboratory in Yokosuka, where I was given the opportunity to work on optical communications systems for about three years. This was the first time that I had been involved in the development of systems-related technology, since I had researched only components and devices up to then. However, I am still using the mindset and outlook that I developed there in my current research. In addition, just hearing about the situation in the United States with regard to the need to reduce power consumption in optical semiconductor devices—which is being researched there in the form of government-supported projects—has motivated me greatly in my work. In particular, it has helped me to see the importance and significance of this research.

I have been invited to a variety of international conferences in recent years, and ideas sometimes come to me from things that I hear at those events. At such times, I promptly email my colleagues or young researchers in Japan involved in photonic device research. I am motivated not just by discussions with specialists but by a variety of things including social phenomena. I have a constant desire to create something new by combining such ideas with technology that I am already knowledgeable about.

In a senior position, however, I must take on more management activities, which limits the time that I can allocate to real research. I therefore have the responsibility to consider the extent to which I myself should contribute to this research and how I should navigate the researchers under me in the right direction.

Nevertheless, I think that it is very important for me as an active researcher to be at the forefront of this research. I would not be able to judge what is crucial just listening to other people and not doing my own research. If I were to lose my edge here, I would not, in the end, be able to use my research time efficiently, and I would not know how to merge all the information I was taking in. However, being too absorbed in my own research would prevent me from receiving information from those around me or leave me with no time for management tasks. Thus, it is important that I strike a balance between what I should do myself and what I should entrust to others.

## Establishing one's core is essential to a researcher

*—By the way, why do you continue to be an active researcher?*

In my younger days, I experienced what it felt like to be completely absorbed in research. Some things can only be understood after making many attempts to solve a problem. This experience involved not only work on intricate and critical problems but everyday failures and mishaps as well. Looking back, I can now laugh at this incident, but once when trying to observe a wafer with a microscope, I accidently damaged the wafer when adjusting the microscope's height. Even science textbooks in elementary school describe the proper way of using a microscope. This simple event demonstrates that sometimes there are things that one should know how to do but can't. Doing even a simple task repeatedly can enhance one's power of judgment and enable one to better understand cause-and-effect relationships or other phenomena based on experience. I feel that the sense of "this is just what is needed" is backed by experience and that one should first become adept at any task you are called to do.

There has recently been talk about the need for researchers to gain experience in other fields such as business or sales to broaden their perspective. However, I would like to have researchers become totally absorbed in their work for about ten years at first to develop their core skills. I think that the number of researchers without such core attributes have been increasing in recent years. If there is no field in which a researcher who has accumulated such a variety of experiences can apply all of them, such experiences have no meaning in the end.

*—Dr. Matsuo, please leave us with a few words for all of our young researchers.*

When you first start out as a young researcher, failure is commonplace. But during that time, you will unconsciously be gaining experience as to where to back off and where to devote all your energy.

Research is indeterminate, unpredictable work, so no one knows just what the results might be. Please take up the challenge that research presents with all your heart! This also means doing work that you will be responsible for above and beyond your duties as a researcher and employee in an organization, although it's still okay to be practical about your work and make time for yourself too.

In cooking, which is one of my hobbies, you usually don't fail as long as you follow the recipe. Research, however, is different; there are no set recipes. Therefore, you, the researcher, must add your own creative touch. Do not lose sight of your original objective and path. Even after a string of failures, you should list your daily achievements within that time and enjoy your research to the fullest.

**■ Interviewee profile**
**Shinji Matsuo**

Senior Distinguished Researcher, Materials and Devices Laboratory of NTT Device Technology Laboratories and NTT Nanophotonics Center.

He received a B.E. and M.E. in electrical engineering from Hiroshima University in 1986 and 1988, and a Ph.D. in electronics and applied physics from Tokyo Institute of Technology in 2008. He joined NTT Opto-electronics Laboratories in 1988, where he researched on photonic functional devices using multiple quantum well pin modulators and vertical cavity surface-emitting lasers. In 1997, he researched optical networks using WDM technologies at NTT Network Innovation Laboratories. Since 2000, he has been researching high-speed tunable optical filters and lasers for photonic packet switching at NTT Photonics Laboratories. He is a member of the Institute of Electrical and Electronics Engineers Photonics Society, the Japan Society of Applied Physics, and the Institute of Electronics, Information and Communication Engineers.

# R&D Trends in Convergence of Photonic and Electronic Hardware for Network Innovation

*Shinichiro Mutoh, Hirokazu Takenouchi, Hideyuki Nosaka, Toshikazu Hashimoto, and Akihiko Miyazaki*

**Abstract**

Network traffic will continue to increase exponentially as we get closer to deploying fifth generation mobile networks, and as the Internet of Things and big data services expand through 2020 and beyond. In these Feature Articles, we look at trends in the research and development of advanced hardware technology designed to achieve substantial increases in the capacity of communication networks with much lower capital and operating expenditures in the next 5 to 10 years. We focus in particular on technology based on new concepts and principles that involve the convergence of photonics and electronics.

*Keywords: photonics-electronics convergence, networks, hardware*

## 1. Introduction

The rapid spread of smartphones around the world is increasing network traffic exponentially. In the next five years, the amount of traffic is expected to increase by a factor of 10 [1]. Development of the fifth-generation mobile network (5G) expected to be launched beginning in 2020 is proceeding rapidly. Specifically, efforts are underway to achieve substantially higher capacity per square kilometer—by a factor of 1000 or more—compared to the present LTE (Long-Term Evolution) system [2].

The movement toward the Internet of Things is also accelerating. One recent key term is *Industry 4.0*, which refers to improving the efficiency of production and services by implementing a cycle of various types of sensing, signal and knowledge processing, and optimization control. Ultimately, the astronomical amount of sensor data on human activity, objects, and the environment will be distributed via the network, and such data will be a source for big data services driven by machine learning.

The virtualization of computations and networks continues to progress, and this means that huge amounts of network traffic will be processed in a cloud environment by enormous datacenters. The Internet protocol traffic of the world's datacenters is expected to triple over the five years from 2013 to 2018, and three-fourths of that is expected to consist of traffic within the datacenters.

## 2. Convergence of photonic and electronic technology: device technology for network innovation

A photonic network is a huge system that combines photonic and electronic technology. It comprises optical transceivers, node equipment (electrical or optical switches or routers), and servers. This equipment is implemented by a combination of electronic and optical hardware. The concept of converging photonic and electronic communication hardware is illustrated in **Fig. 1**. Photonic network communication has evolved through innovation of transmission

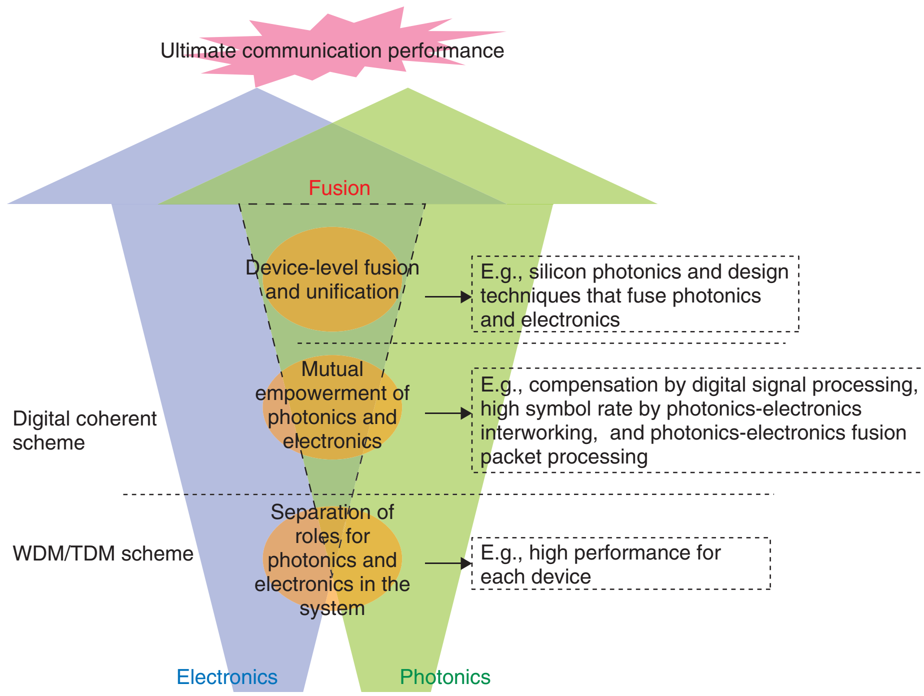



Fig. 1. Fusion of photonic and electronic technology.

technology such as time division multiplexing (TDM) and wavelength division multiplexing (WDM), and through innovation of optical and electrical devices. Digital coherent technology [3] is a revolutionary idea that is enabling communication over 100 Gbit/s per wavelength and over distances of thousands of kilometers. Digital signal processing LSIs (large-scale integrated circuits) constructed using state-of-the-art semiconductor process technology suppress various types of fluctuation and noise in the communication channel, and they have achieved a level of performance that has never been achieved before by individual improvements in optical and electrical devices alone. In the future, the synergistic effect and mutual compensation obtained by combining photonic and electronic technology including digital signal processing may hold the key to even further network innovation.

One direction for progress is device-level convergence. For example, silicon photonics technology is expected to produce a paradigm shift in telecom hardware by increasing its functionality and reducing its size, cost, and power consumption through a high level of integration of optical and electrical devices.

These Feature Articles introduce some of the research and development (R&D) on hardware being conducted at NTT Device Technology Laboratories to achieve network innovation. The first part focuses on cutting-edge technologies for converging photonic and electronic devices, which are aimed at achieving the ultimate in network capacity. The second part describes technology for achieving a radical decrease in cost and power consumption as well as higher capacity. This technology is essential to sustain the progress achieved in networks requiring a much higher level of economy and energy efficiency such as datacenters. We also introduce research on hardware technology to achieve network virtualization in the software-defined networking (SDN) era for reducing capital expenditure (CAPEX) and operating expenditure (OPEX). A mapping of the technology for these two directions is shown in **Fig. 2**.

## 3. Hardware technology for ultimate high capacity: challenge to achieve ultimate high symbol rate

To increase the capacity of photonic networks, technology must expand along three axes: the number of multilevels, the number of subcarriers*1, and the symbol rate*2. For example, recent digital coherent optical communication systems have achieved a

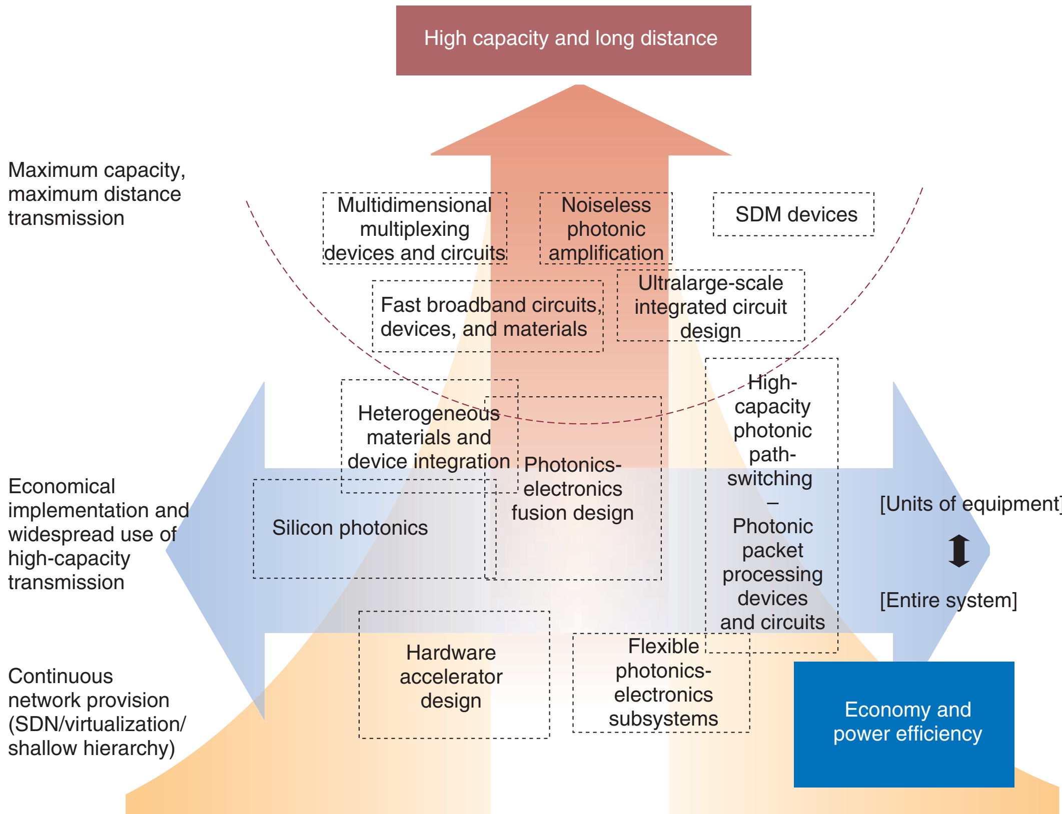



Fig. 2. Hardware technology for the ultimate network.

transmission rate on the level of 400 Gbit/s by using 16QAM (16-level quadrature amplitude modulation)[*3] and two-subcarrier multiplexing [4]. Of the hardware research being done to expand the three dimensions mentioned above, the research aimed at increasing the symbol rate can increase the capacity with the same number of subcarriers and multilevels, so it is advantageous in that it simplifies ultrahigh capacity transceivers. The symbol rate for the current 100-Gbit/s digital coherent systems is 32 Gbaud, but research is ongoing to achieve even higher speeds. The article "High-speed Electronic and Optical Device Technologies for Ultralarge-capacity Optical Transmission" [5] in this issue describes an effort to greatly increase the symbol rate through conversion of ultrahigh speed indium phosphide (InP) integrated circuits and OTDM (optical time-division multiplexing).

### 3.1 SDM technology for drastic increase in capacity

Extensive R&D is being done on space division multiplexing (SDM), which targets a drastic increase in capacity that exceeds the physical limits of conventional single-mode optical fiber [6]. SDM can increase the transmission capacity by a factor of several tens by making maximum use of the spatial degrees of freedom in an optical fiber. This is done by using multicore fiber, which has many cores in a single fiber, or by using multiple waveguide modes within a single core for multimode transmission. The ongoing research toward implementation of SDM includes work on erbium-doped fiber amplifiers (EDFAs) as optical amplifiers for long-distance

*1 Subcarrier: Multiplexed transmission in which a single ultrafast communication channel is divided into optical signals of multiple wavelengths (subcarriers).

*2 Symbol rate: A measurement of modulation speed, also known as 'baud rate.' The unit is sps (symbols/second), but it is often referred to as baud in the field of communications. In multilevel modulation, one symbol can carry multiple bits of information, so the information bit rate is the product of the symbol rate and the number of levels.

*3 16QAM: Quadrature amplitude modulation, in which one symbol is a 4-bit hexadecimal value.

multicore and/or multimode transmission, and connection devices that are required for branching and converging with single-mode fibers, in addition to many-core optical fiber. It also includes signal processing methods for compensating interference between modes within a core [7].

### 3.2 Challenging the Shannon limit: a noiseless optical amplifier

According to Shannon's theory, the capacity of a communication channel is expressed by the following equation,

$$C = B\log_2\left(1 + \frac{S}{N}\right),$$

where $C$ is capacity, $B$ is frequency bandwidth, and $S$ and $N$ are the average signal power and the normal distribution of noise power within $B$. From the equation, we can see that increasing the power of the signal light ($S$) will increase the transmission capacity. However, the nonlinear effect of an optical fiber will cause signal distortion when the input optical power is increased, so the signal-to-noise ratio (SNR) will decrease. Therefore, reducing the noise ($N$) is an important factor in increasing the transmission capacity. With the EDFAs that are currently used in optical telecommunications, however, the introduction of excess noise reduces the SNR of the input signal by half, even in the ideal case.

To cope with this situation, NTT is working on research to improve the SNR by applying phase sensitive amplifier (PSA) technology. A PSA uses parametric amplification by a periodically polled lithium niobate (PPLN)[*4] device, which has a highly nonlinear optical effect. With the PSA, amplification with no degradation of the SNR is theoretically possible, and a doubling of the transmission distance can be expected in theory. This technology is explained in the article "Advances in Phase Sensitive Amplifiers Based on PPLN Waveguides for Optical Communication" [8] in this issue.

## 4. Hardware technology for economical network innovation (towards smaller and more energy-efficient hardware)

### 4.1. Device-level photonics-electronics convergence: silicon photonics

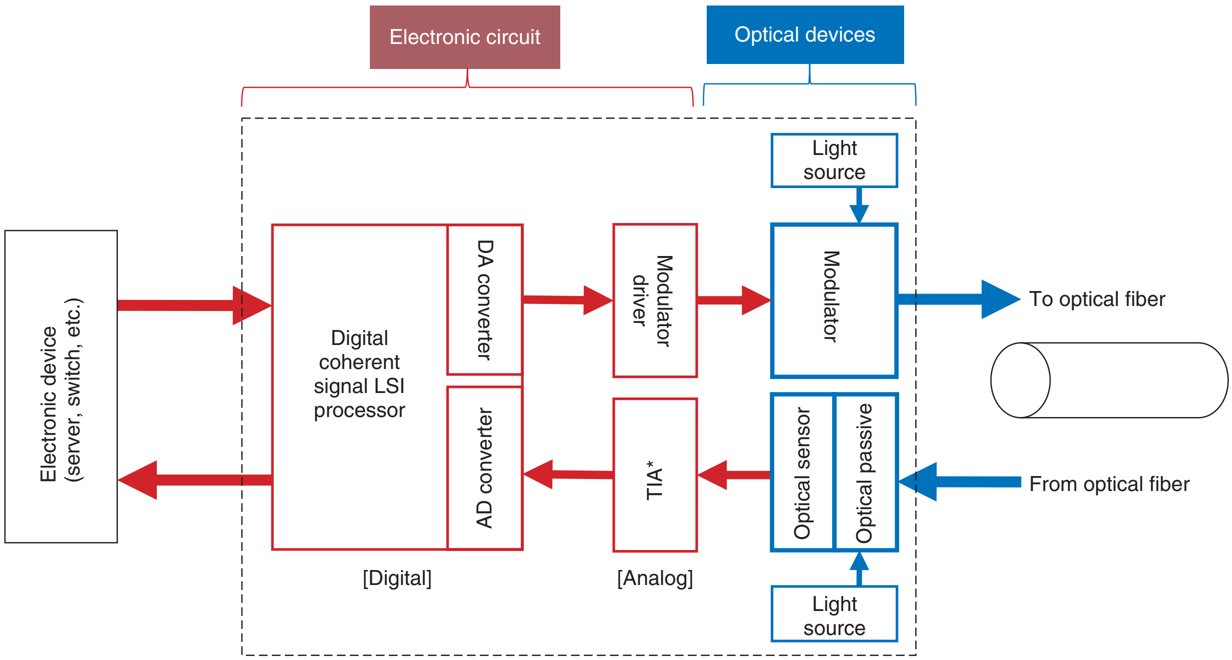
Silicon photonics is technology for integrating electronic circuits and optical circuits/components on a silicon chip. One of its major advantages is that it makes it possible to achieve ultra-compact optical circuits. The dimension of waveguide fabrication and radius of curvature are a few orders of magnitude smaller than for the glass ($SiO_2$) generally used in optical circuits. This can reduce the optical circuit size from centimeter- to millimeter-order. Furthermore, integration with large-scale complementary metal-oxide semiconductor (CMOS) digital circuits with high functionality will lead to an ideal photonics-electronics convergence system-on-a-chip with a smaller, less expensive form.

NTT has been leading the silicon photonics research field and has achieved cutting-edge results for a Si (silicon)-based multiparallel integrated WDM receiver and other advanced devices [9]. The article "Lateral Current-injection Membrane Lasers Fabricated on a Silicon Substrate" [10] explains the cutting-edge optical source integration technology used to integrate a low power consumption InP side-injected thin-film laser on a silicon substrate. The greatest barrier to widespread use of silicon photonics is that the light-emitting capability of silicon itself is very low. We are working to overcome that problem by achieving *true* silicon photonics.

### 4.2. Device-level photonics-electronics convergence: digital mock-up

Complexity in the convergence design is a serious obstacle to radically reducing the hardware cost. The optical transceiver shown in **Fig. 3** comprises both optical and electronic devices. In the conventional design procedure, performance prediction and simple modeling are done only for the optical circuit at first, and the results are input to an electronic circuit simulator to estimate the overall performance. However, performance prediction for a total system is difficult, so repeated test device fabrications are necessary. That process increases the design and manufacturing cost. The article "Photonics-electronics Convergence Design for Digital Mock-up" [11] in this issue describes technology for implementing digital mock-ups that can estimate the convergence hardware performance with high accuracy and without making a series of test devices. In the future, the boundary between photonic and electronic circuits will become blurred in a good sense, both physically and functionally in the silicon photonics era. This technology can be expected to enable design that extracts maximum performance with less cost for photonics-electronics convergence devices.

*4 PPLN: Periodically poled lithium niobate, a non-linear optical material.




*Trans-impedance amplifier, an amplifier that converts the current generated by a light sensor (photodiode) to a voltage signal.

AD: analog-to-digital
DA: digital-to-analog

Fig. 3. Example of optical transceiver.

## 5. Ultrafast optical switching device technology for extending the scalability of datacenters

Large-scale datacenters are used to support cloud computing and big data processing. These datacenters house hundreds of thousands of servers that are connected hierarchically by a large number of network nodes (L2/L3 switches and routers). However, the high latency and huge power consumption of the large numbers and layers of node units are serious problems. Current routers and switches are electronic equipment that consists of integrated circuits. As we approach the limit of Moore's law[*5], it is becoming difficult to solve these problems only by increasing the speed and reducing the power consumption of circuits. The article "High-speed Optical Packet Switching for Photonic Datacenter Networks" [12] describes the innovative research on a photonic implementation of packet-by-packet switching, which has so far been done by conventional electronic routers and switches. Low-latency optical packet switching without opto-electrical conversion is being developed as a solution to these problems. NTT has been leading the world with its cutting-edge research on optical packet switching technology, and has proposed a hybrid opto-electric packet router that combines an ultrafast (nanosecond-order) optical switching device and an electronic buffer (integrated circuit memory).

## 6. Hardware technology for advancing SDN and virtualization

Studies on network virtualization are moving forward with the objective of reducing network CAPEX and OPEX. In network function virtualization (NFV), network functions that have previously been implemented as dedicated hardware are implemented in software that runs on servers. The expected advantages of virtualization include flexible allocation of resources and rapid service provision and modification, as well as reduction of hardware costs [13].

*5 Moore's law: An index for predicting the evolution of integrated circuits proposed by Gordon Moore, one of the founders of Intel Corporation. The law states that the integration density of semiconductor devices will double every 18 to 24 months.

General-purpose servers use the most advanced microprocessors, but the future rate of improvement in semiconductor performance is expected to lag behind the increase in network capacity. As we enter the future terabit era, it is expected to be difficult to obtain speed and power efficiency through the flexibility of NFV. The article “Hardware/Software Co-design Technology for Network Virtualization” [14] in this issue describes hardware accelerator technology as one direction for research on hardware in the era of SDN and virtualization. In that approach, functions that are bottlenecks in improving performance speed are carefully selected and implemented using a more hard-wired method with the objective of raising the cost performance of NFV implemented on general-purpose servers. The acceleration effect was verified by using the Lagopus software switch platform developed by NTT Network Innovation Laboratories [15].

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# High-speed Electronic and Optical Device Technologies for Ultralarge-capacity Optical Transmission

*Hiroshi Yamazaki, Munehiko Nagatani, Toshikazu Hashimoto, Hideyuki Nosaka, Akihide Sano, and Yutaka Miyamoto*

## Abstract

To increase the transmission capacity of optical fiber transmission systems, we have developed a multiplexer-digital-to-analogue converter and an optical time-division multiplexing modulator, which respectively generate high-speed signals in the electronic and optical domains. With these devices, we can significantly increase the capacity per wavelength channel.

*Keywords: DAC, modulator, QAM*

## 1. Introduction

The demand for data transmission capacity is continuing to increase, and to meet this demand, optical transmission systems with per-channel rates exceeding 400 Gbit/s are desired. Several advanced technologies such as multicarrier transmission, high-order multilevel modulation, and high-symbol-rate transmission are expected to be key technologies for achieving a significant increase in capacity. In this article, we describe a multiplexer-digital-to-analog converter (MUX-DAC) and an optical time-division multiplexing (OTDM) modulator, which respectively double the symbol rates in the electronic and optical domains.

## 2. High-speed InP-HBT MUX-DAC

### 2.1 Circuit configuration

Multilevel modulation with a high baud rate is essential for achieving a channel capacity larger than 400 Gbit/s. The MUX-DAC combines the functions of a 2:1 multiplexer (MUX), which doubles the symbol rate, and a digital-to-analog converter (DAC), which converts the input binary (digital) signals to an output multilevel (analog) signal [1]. A functional-block diagram of the fabricated MUX-DAC with 6-bit resolution is shown in **Fig. 1**. The MUX-DAC operates as follows; first, the twelve input digital signals are synchronized with each other and reshaped by twelve D flip-flops (DFFs). Then, the outputs of the six pairs of DFFs are respectively multiplexed by six 2:1 MUXs, which generates six digital signals with a doubled symbol rate. Finally, the outputs of the MUXs are converted to an analog signal with a resolution of 6 bits. Since the frequency of the clock signal input to the DFFs and MUXs is half the symbol rate of the output analog signal, the MUX-DAC is suitable for high-symbol-rate applications. For the DAC section, we employed the R-2R ladder configuration to achieve high-speed operation with low power consumption.

### 2.2 Fabrication and characteristics

We have developed fabrication technologies for indium-phosphide (InP) heterojunction bipolar transistor (HBT) devices, which are promising for high-speed applications in photonic networks [2]. We used

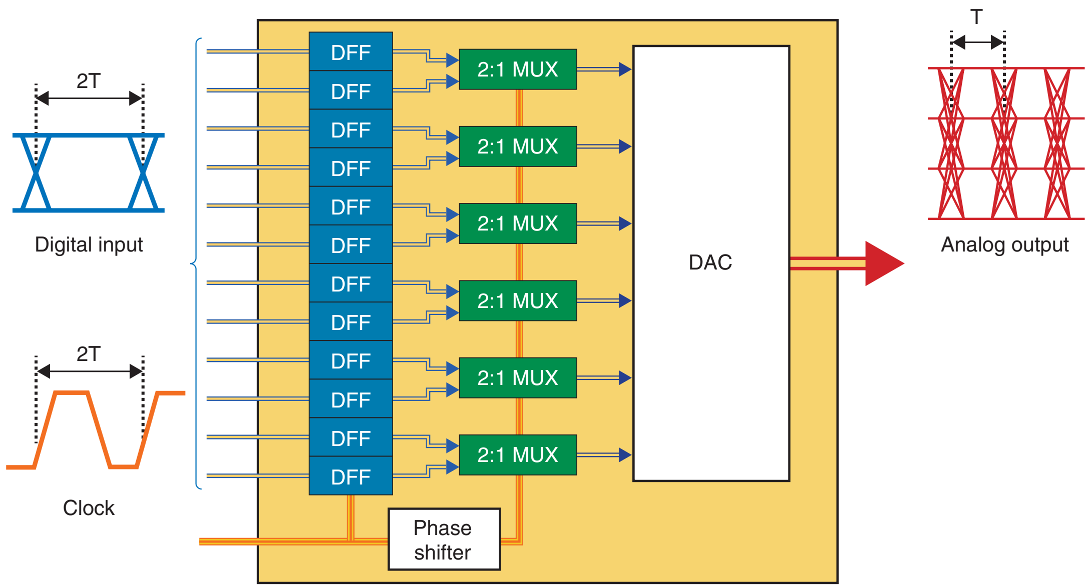


Fig. 1. Block diagram of the MUX-DAC.

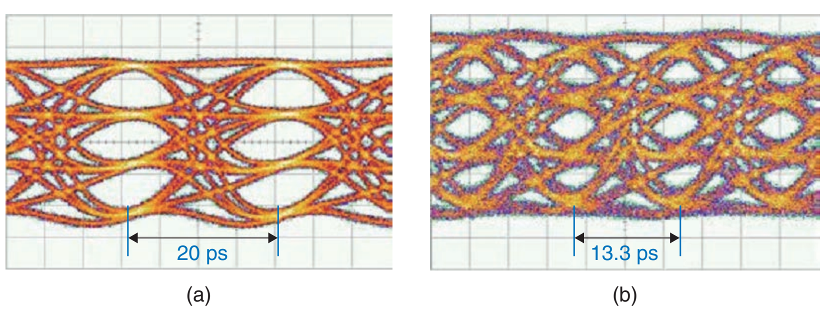


Fig. 2. Eye diagrams of output four-level signals with symbol rates of (a) 50 Gbaud and (b) 75 Gbaud.

our InP HBT process with a linewidth of 0.5 µm to fabricate the MUX-DAC. With this process, we can achieve a very high cutoff frequency (a metric of the operation speed of a transistor) of 290 GHz. Power consumption of the MUX-DAC integrated circuit (IC) is 3.4 W, with roughly 2.9 W consumed in the DFFs and MUXs and only 0.5 W used in the DAC section. The differential output swing voltage is 1 V. The 3-dB bandwidth of the frequency response of the MUX-DAC module exceeds 40 GHz, which is currently the largest value in the world. Eye diagrams of the output four-level (2-bit) signals with symbol rates of 50 and 75 Gbaud are shown in **Figs. 2(a)** and **2(b)**, respectively. Clear eye openings were achieved at a symbol rate as high as 75 Gbaud.

## 3. OTDM modulator with a silica-LN hybrid configuration

### 3.1 Circuit configuration

OTDM technologies have been extensively studied with the objective of breaking the limit of the speed of electronics and generating ultrahigh-speed optical signals. In an OTDM transmitter, each tributary signal (signal to be multiplexed) is shaped into a pulsed waveform to avoid interference between the tributaries. Our modulator, which is designed for an OTDM with two tributaries, combines the functions of a pulse generator and two data modulators [3]. Each data modulator is a dual-polarization optical vector modulator, which is the standard modulator in currently deployed 100-Gbit/s digital coherent systems.

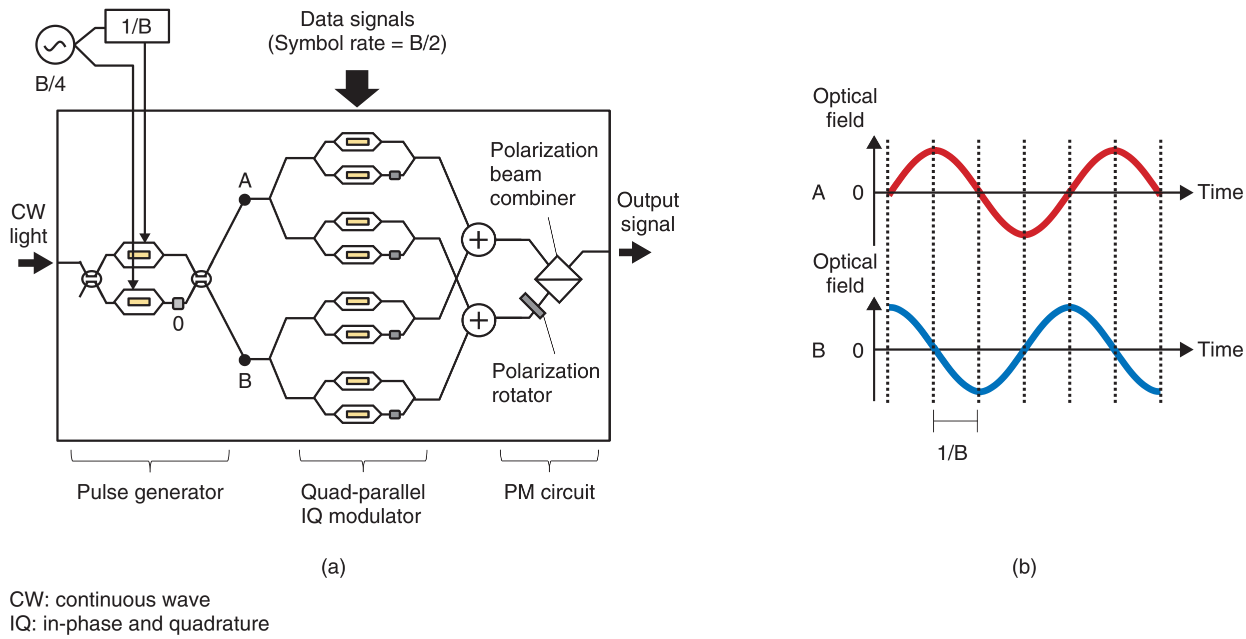


Fig. 3. (a) Optical-circuit diagram and (b) principle of the OTDM modulator.

The OTDM modulator generates the output optical signal with a symbol rate that is double that of each input electronic signal. Unlike conventional OTDM setups, in which a pulsed light source and separate modulators are connected via fiber, the integrated OTDM modulator provides a much smaller footprint and higher stability of the relative optical phase between the tributaries.

The OTDM modulator consists of a pulse generator, four optical vector modulators, and a polarization-multiplexing (PM) circuit, as shown in **Fig. 3(a)**. Each of the two outputs of the pulse generator is bifurcated and sent to two of the four vector modulators. The outputs of each pair of vector modulators connected to different ports of the pulse generator are coupled, and the two coupled pairs are finally multiplexed in the PM circuit with orthogonal polarizations. The pulse generator consists of two Mach-Zehnder modulators (MZMs) connected in parallel with an output 2 × 2 coupler. To obtain a final output symbol rate of B, the two MZMs in the pulse generator are driven with sinusoidal clock signals with a frequency of B/4 and a relative delay of 1/B. Each vector modulator also consists of two parallel MZMs, which are driven with data signals with a symbol rate of B/2. As shown in **Fig. 3(b)**, the intensity peak of the output from one port of the pulse generator always coincides with the extinction of the output from the other port and vice versa. Thus, we can transmit the two tributary signals without inter-symbol interference. Unlike the conventional OTDM with a pulsed light source, which is complicated and provides low spectral efficiency because of the broad spectral bandwidth of the pulse train, our OTDM modulator operates with a simple continuous-wave light source and offers higher spectral efficiency.

### 3.2 Fabrication method and characteristics

To fabricate the OTDM modulator with the complex configuration shown in Fig. 3, we used a hybrid integration of silica planar lightwave circuits (PLCs) and a lithium niobate (LN) chip [4]. The hybrid integration enables us to obtain both high design flexibility for the silica PLCs and a broad electro-optic modulation bandwidth of the LN chip at the same time. The LN chip has ten push-pull pairs of straight phase modulators in an array, which corresponds to the ten MZMs: two for the pulse generator and eight for the four vector modulators (**Fig. 4**). All other passive components such as couplers, static phase shifters, and the PM circuit are fabricated in the PLCs. The pulse generator and the vector modulators are connected via U-turn waveguides to make the module compact. The modulator's static insertion loss for both polarizations is 9.5 dB at a 1550-nm wavelength. All the MZMs have electro-optic 3-dB bandwidths of

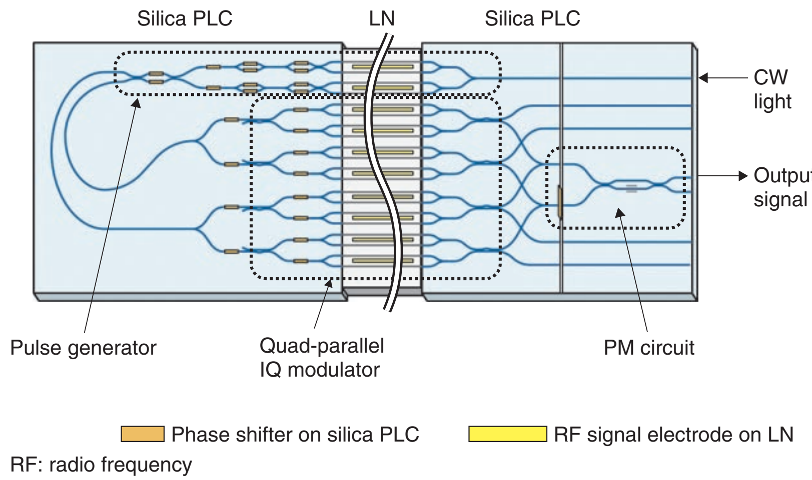


Fig. 4. Configuration of the OTDM modulator.

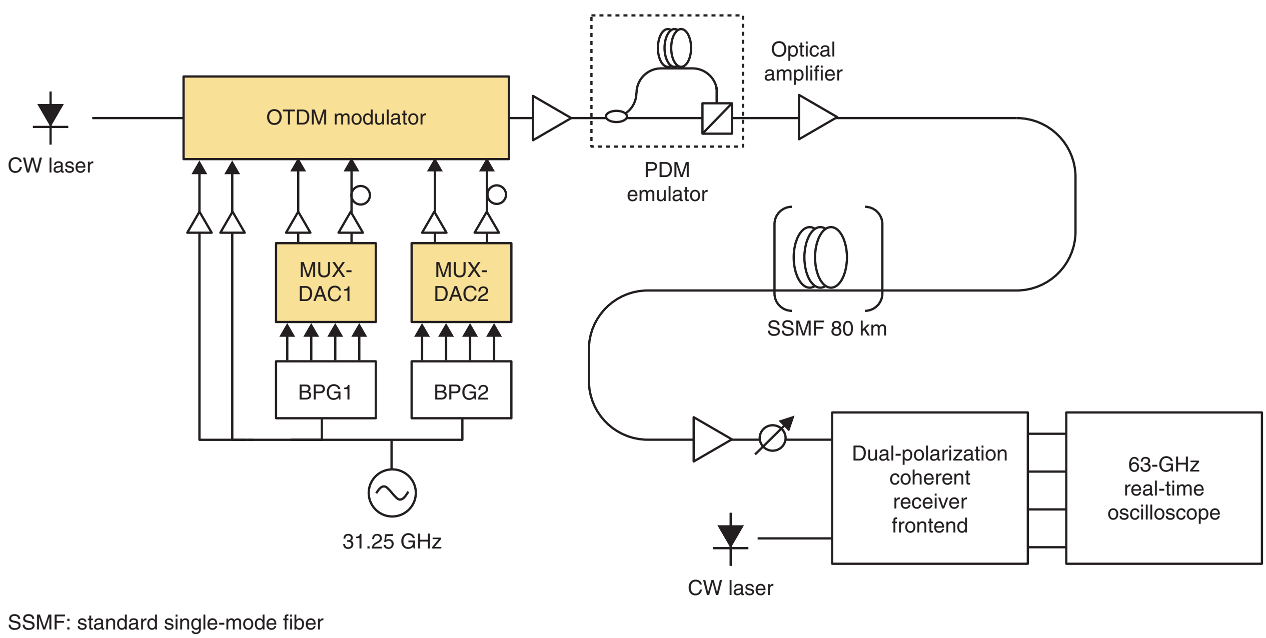


Fig. 5. Experimental setup of signal generation.

~23 GHz. The half-wave voltage of each MZM is ~3.5 V.

## 4. Large-capacity transmission experiment using the MUX-DAC and OTDM modulator

Using the MUX-DACs and the OTDM modulator in combination, we can generate an ultralarge-capacity optical signal [5]. The experimental setup for a 125-Gbaud polarization-division-multiplexed (PDM) 16-level quadrature amplitude modulation (16QAM) signal generation using the two devices is shown in **Fig. 5**. The MUX-DACs converted 31.25-Gbaud binary signals (pseudo-random bit sequences) from bit-pattern generators (BPGs) into 62.5-Gbaud four-level electronic signals, which are used to drive the OTDM modulator to generate the 125-Gbaud 16QAM optical signal. Since only two MUX-DAC

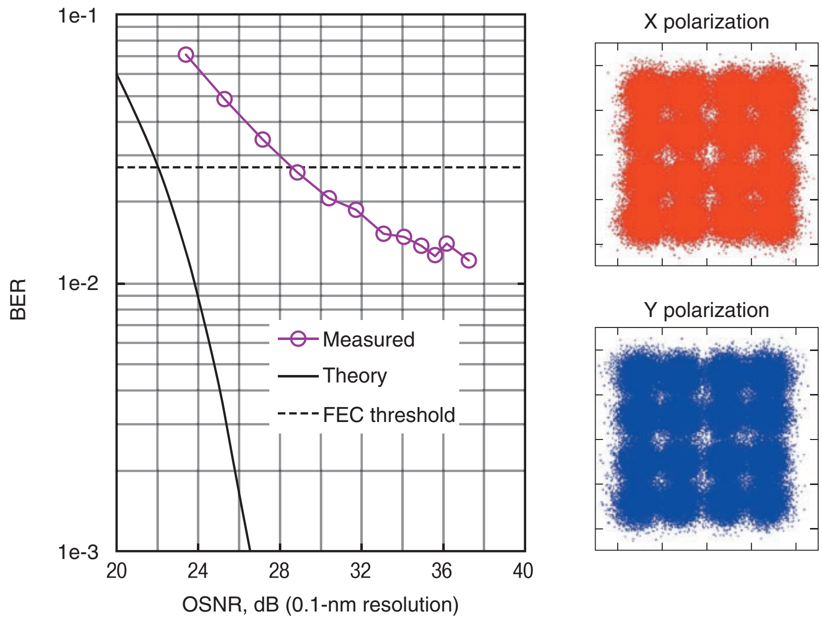


Fig. 6. Back-to-back BER curve and constellations of the 1-Tbit/s PDM-16QAM signal.

modules were available for the experiment, we drove only one polarization channel of the OTDM modulator and generated the PDM signal by using an external emulator. The optical signal was received by a coherent receiver with a 63-GHz real-time oscilloscope and demodulated offline to calculate the bit-error rate (BER).

The measured back-to-back BER versus optical signal-to-noise ratio (OSNR) curve is shown in **Fig. 6**. We obtained BERs below $2.7 \times 10^{-2}$, which is the threshold of the forward error correction (FEC) code with 20% overhead, with an OSNR larger than 28.4 dB. We also tested transmission over 80-km standard single-mode fiber (SSMF) and obtained BERs below the threshold of $2.7 \times 10^{-2}$ with a launched power smaller than +14 dBm. Since the PDM-16QAM signal conveys 8 bits of information per symbol, the gross bit rate of the 125-Gbaud PDM-16QAM signal is 1 Tbit/s. Based on an assumed use of the FEC with 20% overhead, the net data rate is 800 Gbit/s. These values are records for single-carrier optical transmission using a single modulator (with an external PDM emulator).

## 5. Summary

We developed a high-speed InP MUX-DAC and an integrated OTDM modulator with a silica-LN hybrid configuration, which double the respective symbol rates in electronic and optical domains. Using these devices, we successfully demonstrated the first 1-Tbit/s single-carrier optical transmission with a single modulator. These device technologies are promising for future ultralarge-capacity optical transmission systems.

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# Advances in Phase Sensitive Amplifiers Based on PPLN Waveguides for Optical Communication

*Takeshi Umeki, Osamu Tadanaga, Takushi Kazama, Koji Enbutsu, Yutaka Miyamoto, and Hirokazu Takenouchi*

**Abstract**

Drastic improvement of the signal-to-noise ratio (SNR) of optical communication systems is necessary in order to make rapid progress in digital-coherent optical communication technology based on multilevel modulated signals. In this article, we describe the recent progress made in phase sensitive amplifiers (PSAs) based on PPLN (periodically-poled lithium niobate) waveguides. These PSAs are capable of low-noise amplification and both phase and amplitude regeneration, which improves the SNR in optical transport systems.

*Keywords: nonlinear optics, optical parametric amplification, optical signal processing*

## 1. Introduction

The capacity of optical communication systems has been increased in recent years by the improved frequency utilization efficiency achieved with advanced digital-coherent technologies. According to Shannon's theory, a higher signal-to-noise ratio (SNR) of the signal will be required to achieve a higher frequency utilization efficiency of the system. However, the achievable transmission distance and channel capacity are now approaching their limits due to the degradation of the SNR by the accumulation of noise from repeater optical amplifiers and inter-symbol interference caused by nonlinear impairments in the transmission optical fiber [1]. Therefore, a drastic improvement in the SNR is necessary for future optical communication systems.

## 2. PSA using highly efficient PPLN waveguides

A signal-phase-dependent amplification characteristic can be achieved with optical parametric amplification (OPA), which transfers the energy of an intense pump light to the signal light. It amplifies the in-phase component of a signal relative to the phase of the pump and de-amplifies the quadrature component. This phase sensitivity makes it possible to provide several unique features of the phase sensitive amplifier (PSA).

The key feature is that the ideal noise figure (NF) of a PSA is 0 dB [2]; in other words, optical amplification without SNR degradation is possible (feature (1) in **Fig. 1(a)**), whereas the NF of a phase insensitive amplifier (PIA), for example, an erbium-doped fiber amplifier (EDFA), cannot be reduced below the 3-dB quantum limit. Furthermore, a PSA can reduce the phase noise by squeezing the phase because it de-amplifies the quadrature component (feature (2) in

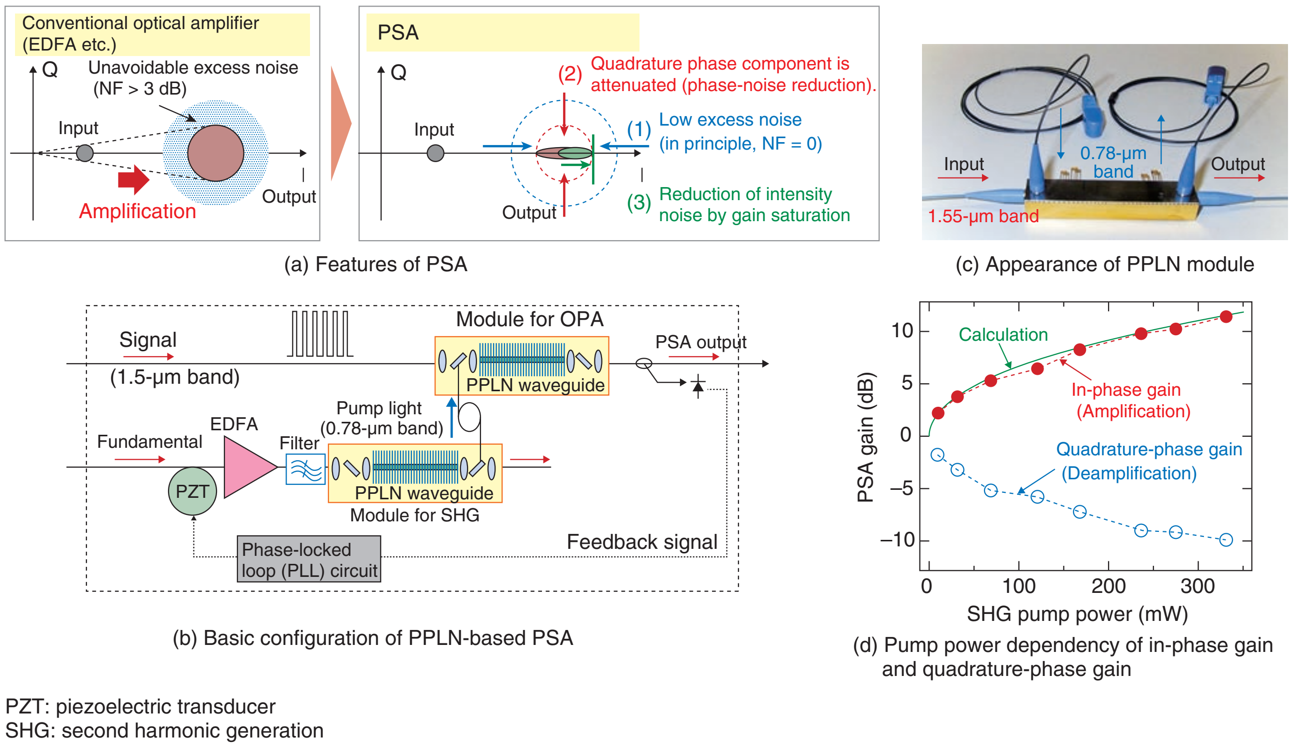


Fig. 1. PSA using highly efficient PPLN waveguides.

Fig. 1(a)). A PSA also provides amplitude regeneration by means of gain saturation thanks to the high-speed response of the parametric process (feature (3) in Fig. 1(a)). Therefore, PSAs are now attracting a great deal of interest for use in enhancing the SNR of inline optical repeater systems because of their potential for low noise amplification and their signal regeneration capabilities.

The basic setup for our recent experimental work on periodically-poled lithium niobate ($LiNbO_3$) (PPLN)-based PSAs is shown in **Fig. 1(b)**. Two PPLN waveguides were used for second harmonic (SH) pump generation and OPA, respectively. High conversion efficiency and high power tolerance are both desirable in order to achieve a high parametric gain. We developed PPLN ridge waveguides using the direct bonding method, which made the waveguides highly resistant to photorefractive damage [3]. We used the dry etching technique to obtain a ridge waveguide with fine uniformity, which yielded high SH conversion efficiency. Recent advances in PPLN waveguides and related module packaging technology have enabled us to explore $\chi(2)$-based PSAs for optical communication [4].

The PPLN waveguides were assembled into fiber-pigtail modules. The modules have four input/output ports to allow SH pumping. To achieve a stable PSA output, an optical phase-locked loop (PLL) is used to compensate for the slow relative phase drifts between the signal and SH-pump lights. A photo of the module is shown in **Fig. 1(c)**. Polarization-maintaining fibers for 1.55 and 0.78 μm were respectively used in the two signal ports and the two pump ports. The signal and SH pump were combined with a dichromatic mirror and injected into the waveguide inside the module. The module packaging technology enabled us to achieve both low insertion loss and stable operation.

The in-phase gain and quadrature-phase gain as a function of the SH pump power is shown in **Fig. 1(d)**. By increasing the SH pump power, the in-phase gain was increased and the quadrature-phase gain was decreased symmetrically. A gain over 10 dB was obtained, and the pump power dependence agreed well with the theoretical curve. Nearly perfect phase sensitive amplification characteristics were obtained because the ridge waveguide provides a sufficient spatial mode overlap between the signal and SH pump light, and temporal mismatching is prevented thanks to continuous wave pumping.

Probably the most intriguing property of a PSA is

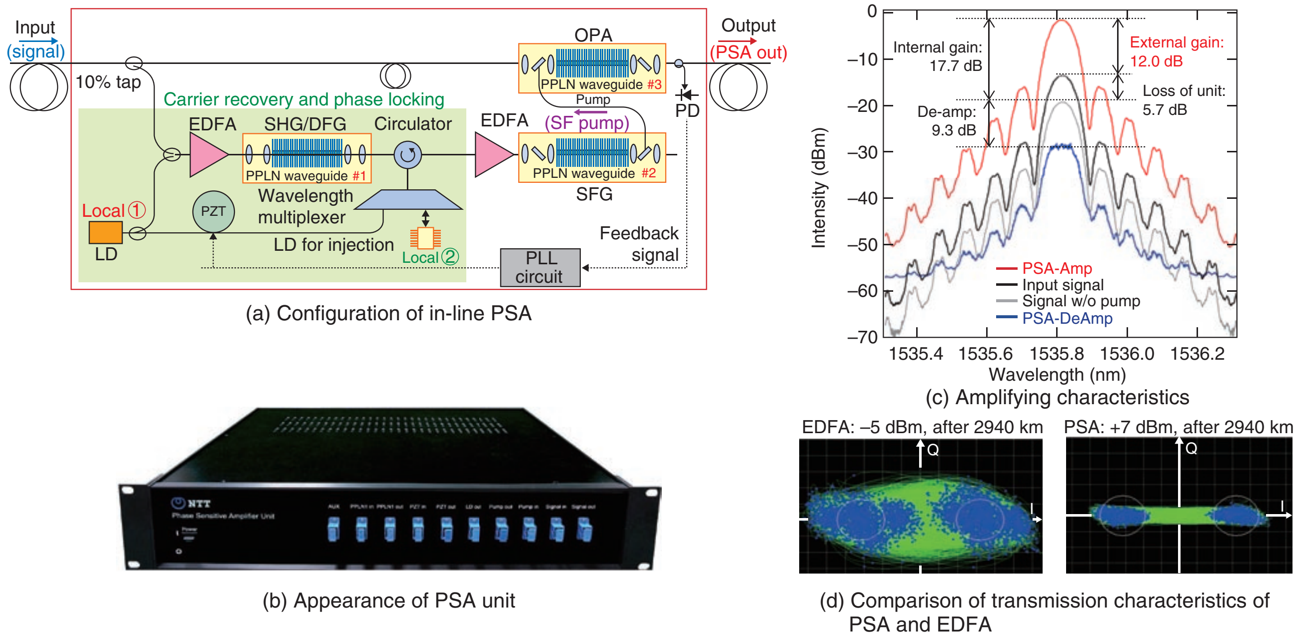


Fig. 2. Multi-repeater transmission using amplitude and phase regeneration of in-line PSA.

the '0 dB' quantum-limited NF. We evaluated the NF of a degenerate PSA, where the signal and an idler were the same wavelength. We confirmed the low noise characteristics in which the NF values of the PSA were 1.8 dB, which is below the standard quantum limit of 3 dB, by using an optical and an electrical spectrum analyzer [5]. We believe the measured NF was largely due to the extrinsic coupling loss; therefore, the intrinsic NF was very close to 0 dB.

## 3. Multi-repeater transmission using amplitude and phase regeneration by in-line PSA

In addition to its capacity for low NF amplification, a PSA has a phase and amplitude regeneration capability that is achieved by using the phase squeezing property and by operating the amplifier in the saturated regime. These capabilities mean that PSAs will have a large impact on long-haul transmission if they are used as multiple repeaters. For the repeater operation of the PSA, the phase of the pump should be locked to that of the input signal. The configuration of an in-line PSA for a binary phase shift keying (BPSK) signal using a carrier-recovery and phase-locking system is shown in **Fig. 2(a)**. The tapped signal is converted to SH light in the PPLN waveguide. Doubling the signal phase makes it possible to recover the carrier from a BPSK signal without a carrier component. The carrier phase is copied to the 1.5-μm-band idler wave by the difference-frequency generation (DFG) process. Then the recovered carrier phase is locked by injecting the idler into a local laser. The in-line PSA, which operates as a repeater amplifier, is achieved using the phase-locked local light.

The key components in Fig. 2(a), including the three PPLN modules, an LD (laser diode) for injection, and a PZT (piezoelectric transducer) for the PLL, were assembled into a PSA unit as shown in **Fig. 2(b)** to obtain stable operation. We obtained a high external gain of 12 dB for a BPSK signal using the in-line PSA as shown in **Fig. 2(c)**.

We also examined the regeneration capability of the in-line PSA in a multi-span transmission. A comparison of the transmission performance for both the PSA and an EDFA at the same link is shown in **Fig. 2(d)**. The left constellation is for the EDFA link after about 3000-km transmission in an optimal power condition. The signal quality was degraded by amplified spontaneous emission (ASE) noise and fiber nonlinearity. However, thanks to the phase and amplitude regeneration capabilities of the PSA, the inter-symbol interference caused by the phase noise resulting from fiber nonlinearity and the intensity noise caused by the ASE of an optical amplifier are largely suppressed, as shown in the right constellation.

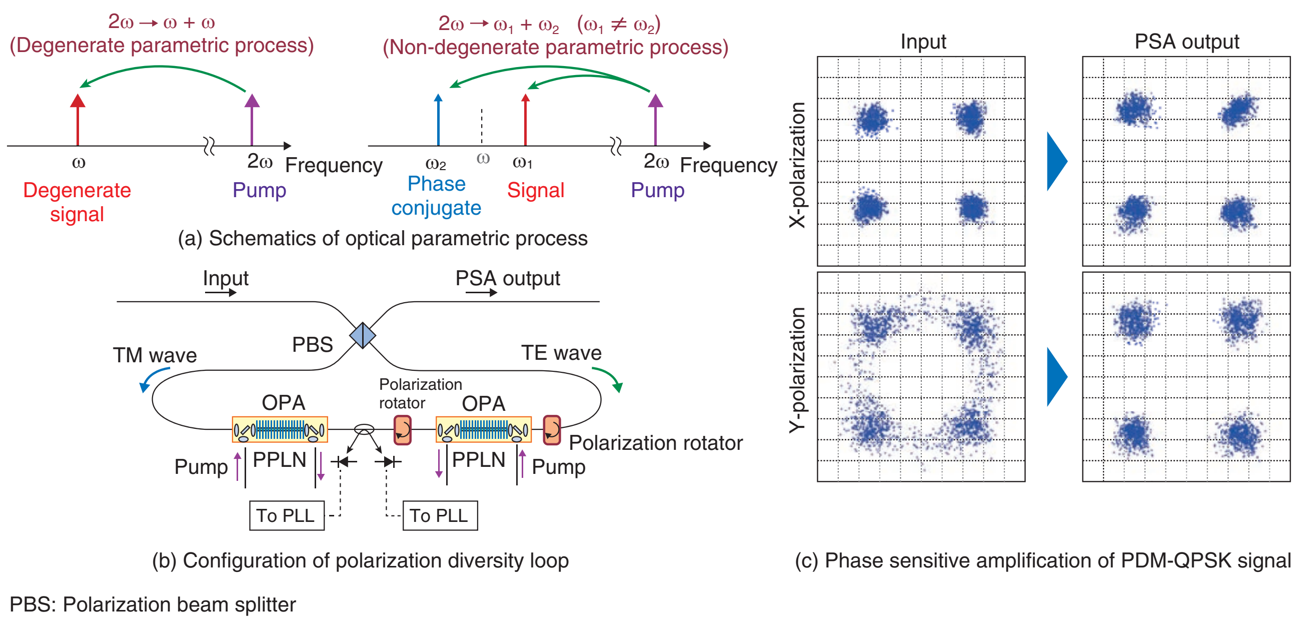


Fig. 3. Multilevel phase coded and PDM signal amplification.

## 4. PSA for multilevel phase coded and polarization-division multiplexed signal

The in-line PSA using degenerate parametric amplification mentioned above can only handle a binary modulated signal. The high capacity communication of the future will most likely operate with spectral efficiencies greater than 1 bit/s/Hz, thereby requiring the use of multilevel phase coding and polarization-division multiplexing. Extending the applicability to a polarization-division multiplexed (PDM)-QAM (quadrature amplitude modulation) signal is practically very important in order to install the PSA in a practical system based on digital-coherent technologies. For the OPA process, energy is transferred from a pump light with a frequency of 2ω to a signal light and an idler light with frequencies of $\omega_1$ and $\omega_2$. When $\omega_1 = \omega_2$, the process is said to be degenerate, and when $\omega_1 \neq \omega_2$, the process is said to be non-degenerate (see **Fig. 3(a)**). For the non-degenerate process, a multilevel-modulation signal can be handled by using a phase conjugate signal as the idler.

Moreover, a polarization diversity scheme is required to handle the PDM signal because a second-order nonlinear optical medium such as PPLN is usually polarization dependent. A schematic view of the proposed polarization diversity loop configuration is shown in **Fig. 3(b)**. In this setup, the two waveguides are arranged in series, and a rotator is installed between them. The configuration combines the advantages of being free of delay alignment and having low reflection noise. Although the loop configuration was used to achieve polarization diversity without any delay adjustment, the TM (transverse magnetic) and TE (transverse electric) waves are independently amplified by two different waveguides.

The capability of amplification for multilevel-modulated and PDM signals was confirmed by using the non-degenerate process and the diversity configuration. The transmitter generated a 20-Gbaud quadrature phase shift keying (QPSK) signal, and a phase-conjugated idler was generated by DFG. After the DFG process, a PDM emulator was used to generate an 80-Gbit/s PDM-QPSK signal with a phase conjugated idler. A $LiNbO_3$ phase modulator was used to add phase noise to confirm the phase regeneration capability of the PSA. Constellation diagrams for an 80-Gbit/s PDM-QPSK input signal with phase noise and the output signal after using the PSA are shown in **Fig. 3(c)**. The constellation for the Y-polarization of the input signal indicates that larger phase noise was induced than that for the X-polarization because of the polarization dependence of the $LiNbO_3$ phase modulator. The constellation points were rotationally spread due to the large phase noise. After using the PSA, a major phase noise reduction was achieved with the canceling effect. The phase sensitive amplification of the PDM-QPSK signal was confirmed from the inherent noise canceling characteristics of the PSA.

## 5. Conclusion

We introduced PSAs based on PPLN waveguides that have capabilities of low noise amplification and both phase and amplitude regeneration for improving the SNR in optical transport systems. We will contribute to further expanding the capacity of future backbone optical communication systems by maximizing the potential of digital-coherent technologies.

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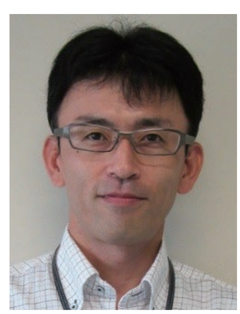

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# Lateral Current-injection Membrane Lasers Fabricated on a Silicon Substrate

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## Abstract

NTT has developed lateral current-injection membrane lasers fabricated on silicon for short-reach optical interconnections. The lasers are fabricated using the crystal growth technique on a bonded substrate consisting of compound semiconductors and silicon. Integration of the lasers and silica-based waveguides has also been achieved recently. In this article, we introduce directly modulated lateral-current injection membrane lasers and their integration with silica-based waveguides.

*Keywords: semiconductor laser, silicon photonics, photonic integrated circuit*

## 1. Introduction

The power consumption in information and communication technology devices has reached a critical level with the explosive increase in network traffic. The power dissipation in large-scale datacenters is estimated to exceed 1% of all power consumption. It is therefore essential to cut the power consumption of both networks and devices. Data transmission within datacenters consumes 70% of all network traffic handled by datacenters [1]. Optical interconnection, in which the electrical data transmission is replaced with optical data transmission, has been actively developed to reduce datacenter power consumption. Vertical cavity surface emitting lasers (VCSELs) have already been commercialized as the transmitters for intra-rack and inter-board data transmission. Furthermore, optical links for intra-chip data transmission are also attracting attention because the performance of chip-to-chip and intra-chip data transmission for large-scale integrated circuits is facing the limit.

To introduce optical links into short-reach data transmission, it is critical to reduce the power consumption and large-scale integration of optical devices, including transmitters and receivers. Wavelength division multiplexing (WDM) is a promising technology to realize large-capacity and low-cost optical links. However, the VCSELs currently used in optical interconnections are inappropriate for single-mode transmission and the WDM network. It is thus essential to achieve high-density integration of single-mode lasers such as distributed feedback (DFB) lasers in order to introduce the WDM network into short-reach optical interconnections.

Efforts to achieve high-density integration include the development of silicon photonics to realize low-cost and high-density optical device integration on large-diameter silicon wafers [2]. The use of silicon photonics is expanding from passive components such as optical waveguides and filters to active components such as modulators and germanium-based photodiodes. In addition, the fusion of optical and electronic circuits is promising. Transceivers

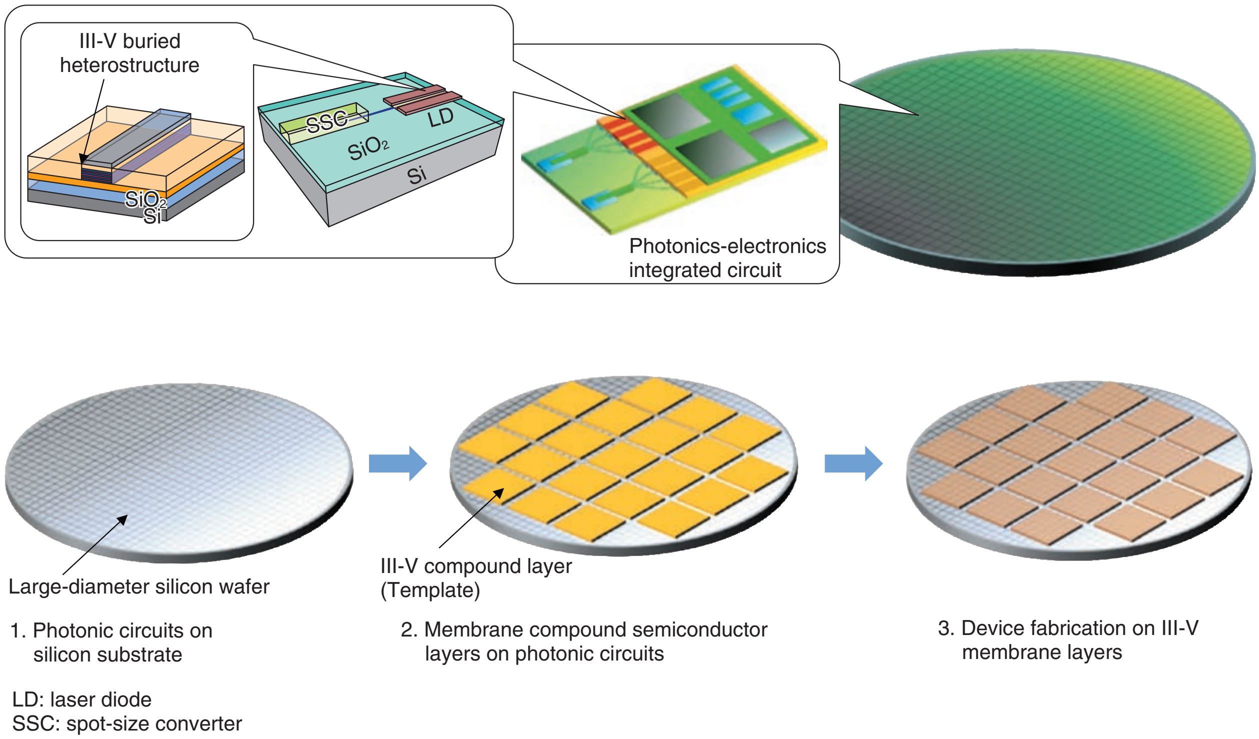



Fig. 1. Concept of laser integration on a silicon wafer and photonics-electronics integration.

consisting of silicon optical devices and CMOS (complementary metal-oxide-semiconductor) transistors integrated on silicon wafers have already been commercialized.

Meanwhile, the integration of lasers on silicon remains a challenge. Silicon is an indirect transition semiconductor; it is not appropriate for light sources because of its extremely low emission efficiency. Some approaches have been proposed to achieve emission of silicon-based materials. These approaches include adding impurities, enhancing the emission rate by using fine structures, and using germanium-based lasers.

However, commercialized lasers have not been achieved yet. The standard approach is hybrid integration of compound semiconductor-based lasers and silicon-based optical devices. The commercialized transceivers still employ semiconductor lasers as extra light sources. There are two ways of achieving hybrid integration: laser bonding on silicon optical circuits, and laser fabrication on compound semiconductor active regions bonded on silicon waveguides. The former approach requires fine alignment between the lasers and silicon waveguides with submicron order accuracy. This requirement will raise the fabrication cost as the integration density increases.

In the latter approach, laser waveguides are determined by the silicon waveguide; therefore, the alignment accuracy of bonding processes is eased. However, it is difficult to achieve compact lasers because the optical confinement in the active layer is low; most optical power is confined in the silicon waveguides. Therefore, it is essential to make progress in both the fabrication process and the development of the laser structure in order to realize high-density integration of lasers with low-power consumption on silicon substrates.

## 2. Integration of compound semiconductors on a silicon substrate

NTT has developed novel techniques to integrate semiconductor lasers on silicon. The concept of the integration is shown in **Fig. 1**. First, silicon photonic circuits are fabricated on a large-diameter silicon dioxide and silicon ($SiO_2$/Si) substrate. Next, membrane compound semiconductor layers are bonded on the silicon photonic circuits. We call this bonded compound semiconductor layer a template. The lasers are fabricated on this template. The lasers can

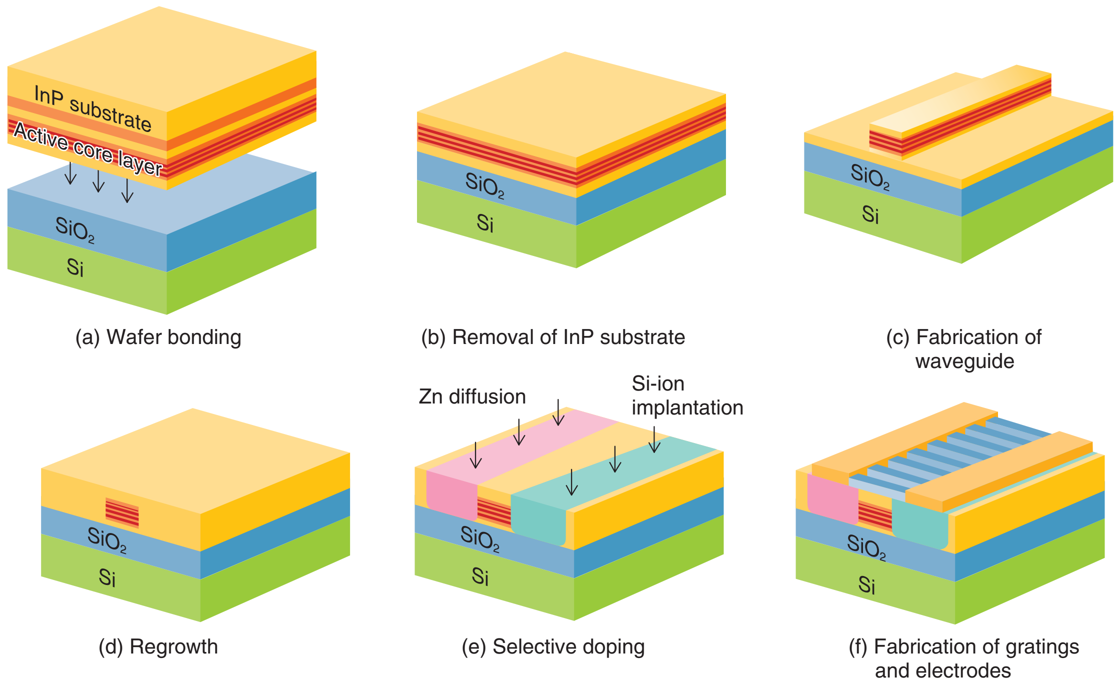


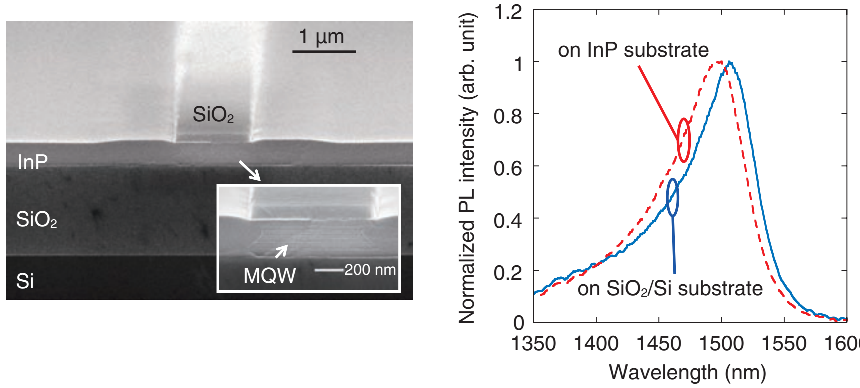

Fig. 2. Membrane laser fabrication process.

be fabricated by using alignment marks made on a silicon substrate. It is easy to achieve fine alignment between the silicon waveguides and the lasers. This technique will enable high-density integration of all optical devices on a large-diameter silicon wafer. With further development of the integration of photonic and electronic circuits, it will be possible to achieve compact transceivers on a large-scale silicon wafer.

The process used to fabricate the membrane lasers is shown in **Fig. 2**; it is the same as that described in our previous reports [3–4]. An active layer is grown on an indium phosphide (InP) substrate to be bonded with an $SiO_2$/Si substrate. The InP-substrate is removed to form a membrane layer. The buried heterostructure (BH) is formed by means of waveguide etching and crystal regrowth on the template. The lateral current injection structure is formed by selective impurity doping. Electrodes and Bragg gratings are formed on the surface of the laser. This laser features high optical confinement in the active region thanks to the large difference in the refractive index between $SiO_2$ and the thin compound semiconductor layers. In addition, the BH provides strong carrier confinement in the active region to enhance the carrier-photon interaction. This feature contributes to reducing the footprint and power consumption of lasers [5]. We previously reported the energy cost of 171 fJ/bit, which was the smallest value of all DFB lasers [6]. These approaches enable the high-density integration of silicon optical circuits and high-performance lasers on a silicon wafer.

## 3. Membrane lasers on a silicon substrate

We fabricated the lasers using the fabrication process described in the previous section [7]. The most challenging step is growing the crystal on the bonded wafer consisting of silicon, $SiO_2$, and compound semiconductors. The environmental temperature varies between room temperature and 600˚C during the fabrication process. Meanwhile, the thermal expansion coefficients of the silicon, $SiO_2$, and InP are different. This difference causes thermal stress in the epitaxial layer during the fabrication. The stress could cause serious defects in the active region, which would degrade the lasing characteristics. We were able to suppress the effect of thermal stress by using a thin InP-based template. The critical thickness of the InP layer was theoretically estimated to be 430 nm to achieve crystal growth under the temperature variation during the fabrication process. This thickness is sufficient to realize optimized membrane lasers. We used a 250-nm-thick InP-based template to




(a) (b)

PL: photoluminescence

Fig. 3. (a) Cross section and (b) photoluminescence spectra of BH fabricated on $SiO_2$/Si.

fabricate the lasers.

The template is fabricated using a 2-inch-diameter thermally oxidized silicon wafer and an InP wafer. The active layer, consisting of six InGaAsP (indium gallium arsenide phosphide)-based quantum wells, is grown on an InP substrate by metal-organic vapor phase epitaxy (MOVPE). Covalent bonding assisted by $O_2$ plasma is used to bond the epitaxial layer and the $SiO_2$/Si wafer. After the bonding process, the BH is fabricated by chemical etching and MOVPE regrowth. The p-i-n diode structure is formed by Si-ion implantation for n-doped regions and Zn thermal diffusion for p-doped regions. The surface grating is patterned on the 130-nm-thick $SiO_2$ layer above the active region waveguide. A cross section of the fabricated BH is shown in **Fig. 3(a)**. The active region was successfully buried with the InP layer. No cracks or dislocations are observed. The photoluminescence spectrum of the fabricated BH on the $SiO_2$/Si layer is shown in **Fig. 3(b)**. The emission spectrum of BH active layers grown on InP is superimposed. The spectra are almost the same; no serious degradation is observed after the laser fabrication. These results verify that our approach is applicable to laser fabrication.

We fabricated the DFB laser by using this active layer. The laser cavity is formed by the surface grating and etching mirrors at the facets. The coupling coefficient of the grating was designed to be 150 $cm^{-1}$. Single-mode lasing with a side mode suppression ratio over 40 dB is observed. The current-output power characteristics of the fabricated laser with a cavity length of 120 µm are plotted in **Fig. 4(a)**. The threshold current was 1.8 mA. Lasing without kinks is observed at temperatures up to 100°C. An eye diagram of 40-Gbit/s direct modulation is shown in **Fig. 4(b)**. The bias current and modulation voltage were 15 mA and 1.31 V, which corresponds to an energy cost of 848 fJ/bit. The modulation efficiency was 6.0 $GHz/mA^{0.5}$. This is the first 40-Gbit/s direct modulation of membrane lasers.

The integration of the lasers and silicon/silica-based waveguide is a significant step forward toward realizing photonic integrated circuits on silicon. A distributed reflector (DR) laser integrated with a spot-size converter (SSC) and a $SiO_x$ waveguide [8] is shown in **Fig. 5(a)**. The DR laser consists of a front DFB section and a rear distributed Bragg reflector (DBR) section. The rear DBR mirror suppresses the output from the rear section, which can enhance the effectiveness. A compact cavity can be achieved by employing a DBR with high reflectivity. The BH active region has almost the same structure as that of the previous DFB laser. The surface grating is patterned on the InP surface above the DFB and DBR section. The coupling coefficient is designed to be 1500 $cm^{-1}$. The SSC section consists of an InP tapered waveguide section covered with the output $SiO_x$ waveguide and is formed in front of the DR laser. The laser beam, strongly confined in the BH active region, spreads in the tapered region to convert into the propagation mode of the $SiO_x$ waveguide. The DFB length and the SSC taper length are 50 µm and 300 µm, respectively. The measured coupling between the laser and optical fiber is 2.7 dB, which is almost 6 dB smaller than the coupling between the

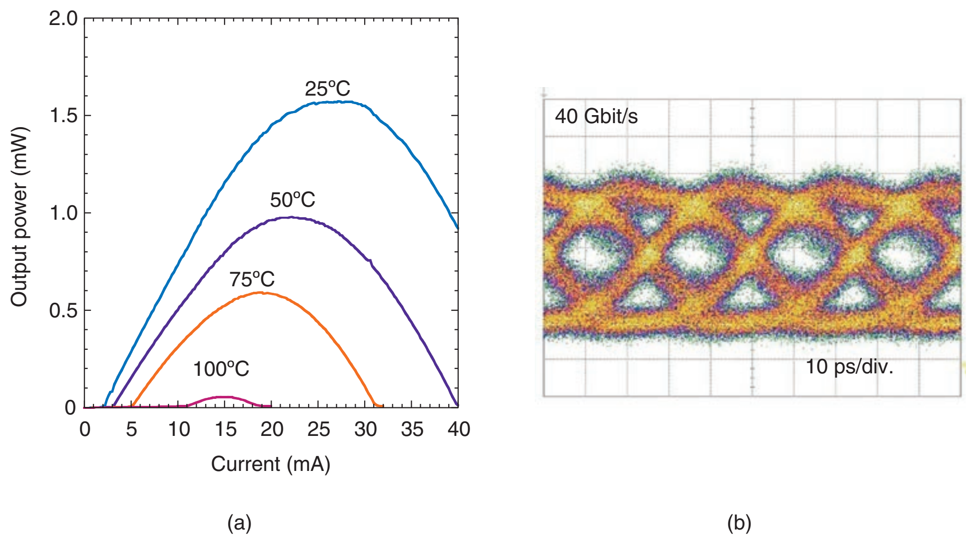



Fig. 4. (a) Current-output characteristics and (b) modulation waveform of membrane laser integrated on silicon.

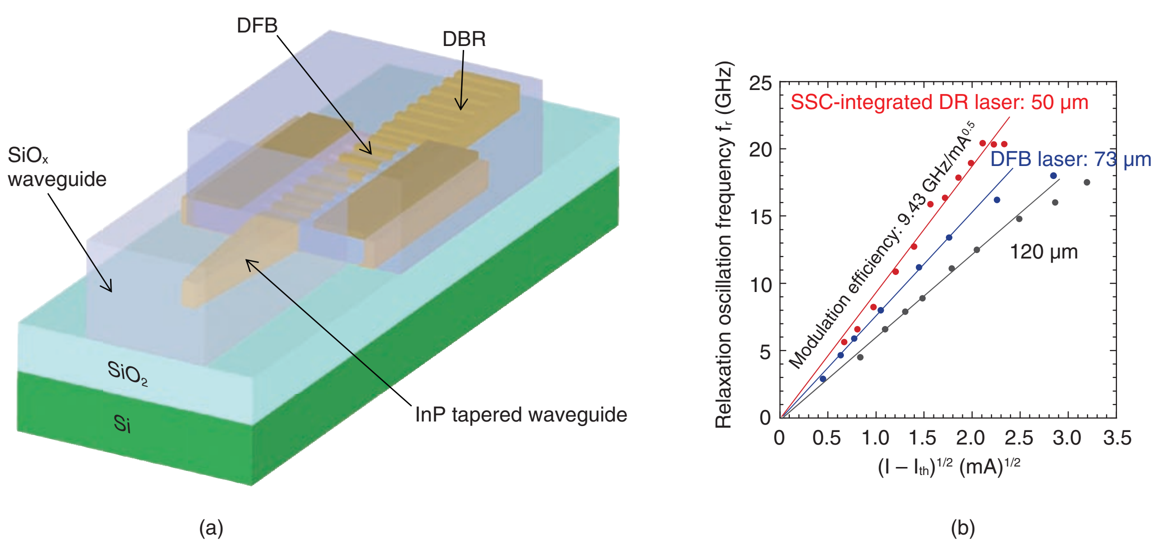



Fig. 5. (a) Structure of SSC-integrated membrane laser and (b) modulation efficiency of membrane lasers.

laser without the SSC and a lensed fiber. The modulation efficiency of the fabricated lasers integrated on silicon is plotted in **Fig. 5(b)**. The DFB lasers with cavity lengths of 73 μm and 120 μm, and the DR laser with a cavity length of 50 μm are compared. The modulation efficiency of the DR laser was enhanced to 9.43 GHz/mA$^{0.5}$ thanks to the short cavity. The energy cost was also improved to 132 fJ/bit under the modulation speed of 25.8 Gbit/s.

## 4. Summary

We reported the development of semiconductor lasers fabricated on a silicon substrate. The crystal growth on the bonded wafer makes it possible to achieve membrane lasers operating with low power consumption comparable to VCSELs. We also successfully integrated the laser and the silica-based waveguide with high coupling efficiency. Our next challenges are to achieve high-density integration of the lasers and a larger wafer size. The integration of light sources and silicon optical circuits would greatly expand the application area of silicon photonics. These technologies would pave the way to achieving large-scale optical circuits for optical interconnections. The ultimate target in the future is the integration of electronics and optical circuits.

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# Photonics-electronics Convergence Design for Digital Mock-up

*Kotaro Takeda, Kentaro Honda, Hideyuki Nosaka, Hiroshi Fukuda, and Tsuyoshi Yamamoto*

## Abstract

We developed a design technique for an electronic and photonic integrated circuit that involves using an equivalent circuit of optical devices in an electrical circuit simulator. Key features are the use of structural and physical parameters as calculation parameters in the equivalent circuit to provide a practical device design and the use of an intermediate frequency to model the wavelength dependence of optical devices in an electrical circuit simulator. By combining these techniques, we simulated the bit error rates and eye diagrams of a device that integrates an optical and electrical circuit. This technique turns an electrical circuit simulator into a photonics-electronics convergence simulator.

*Keywords: photonics-electronics convergence, digital mock-up, equivalent circuit*

## 1. Introduction

### 1.1 Photonics-electronics convergence

Telecommunications network systems are now facing an explosive traffic increase, with a growth rate of 30% per year [1]. At this growth rate, the power consumption and capital/operating expenditures for network systems will increase by ten times or more. One of the breakthrough technologies for dealing with this information explosion is photonics-electronics convergence. Photonics-electronics convergence devices, which comprise both optical and electrical components, can achieve performance that far exceeds that of discrete devices. Moreover, their high integration density and low power consumption make them promising devices for reducing network costs [2–4].

Photonics-electronics convergence devices are more than just combinations of electrical and optical circuits. They involve high-density integration that provides organized functions and high performance. Thus, a photonics-electronics convergence device must comprise integrated circuits. However, dense and functional integration leads to complex designs and high fabrication costs.

To reduce fabrication costs, we need to estimate the performance of an integrated circuit before it is fabricated. For this purpose, NTT Device Technology Laboratories has focused on developing a technique to design photonics-electronics convergence. Conventionally, optical and electrical devices are designed individually to obtain the optimal performance of an integrated device, as shown in **Fig. 1(a)**. However, as mentioned above, the actual performance of integrated devices does not correspond to the performance of the combined discrete optical and electrical devices. For this reason, optical and electrical devices should be designed in a cooperative manner by converting and sharing data to maximize the total performance of integrated devices.

However, the potentially very large computational cost of data conversion and sharing could become a bottleneck in the overall design. Furthermore, in the data sharing process, each design tool can only share limited information such as output waveforms, scattering parameters, and DC (direct current) and AC (alternating current) responses. This limitation impedes the overall design, which increases the time and cost. In addition, many software licenses are required, which increases the capital cost for the design.

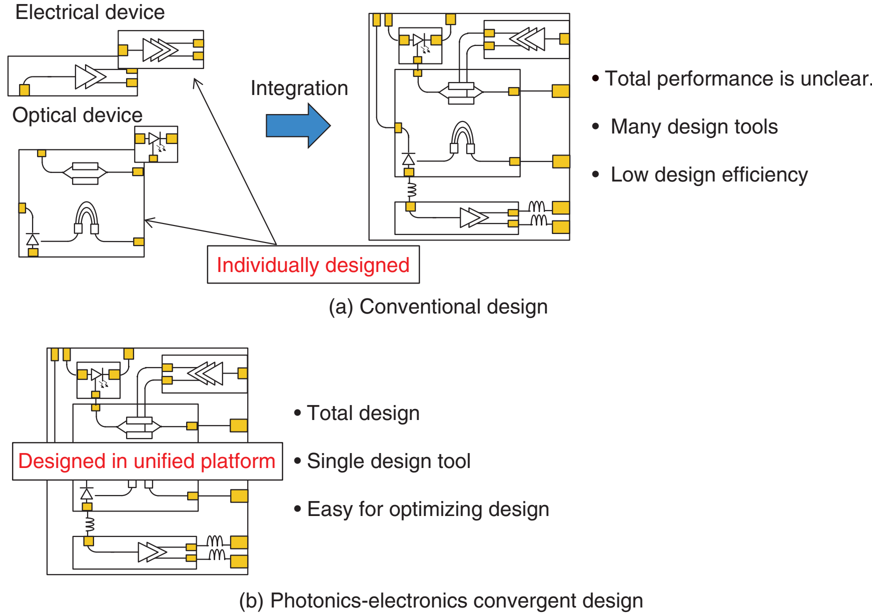



Fig. 1. Comparison of conventional design and photonics-electronics convergent design.

### 1.2 New design technique

NTT Device Technology Laboratories has devised a photonics-electronics convergence design technique to solve these cost problems. The design involves the use of a unified platform to design both optical and electrical devices and simulate overall performance (**Fig. 1(b)**). This approach eliminates the need for data conversion/sharing and software licenses and guarantees that information about devices is not lost. In other words, it reduces the computational and capital costs, as well as the required time. This design technique, referred to as a digital mock-up, uses precise design and simulation models that reduce the number of trial fabrications to zero. As a final objective of the photonics-electronics convergence design, we aimed to construct a digital mock-up for a photonics-electronics convergence device.

The first step in providing the digital mock-up was to use an electrical circuit simulator as a unified design platform. This eliminates the need for an optical device simulator and enables us to design everything in one simulator. This unified platform is familiar to people in the electrical circuit field and is compatible with electronic design automation. Since a photonics-electronics convergence device has many more electrical elements than optical ones, the use of an electrical circuit simulator as a unified design platform is efficient from the viewpoint of computational cost.

There are two important points for modeling optical devices in an electrical circuit simulator. One is that the models should be able to handle the physical and structural parameters for designing them. The other is that the electrical circuit simulator must handle characteristics that cannot be used as calculation parameters in a conventional electrical circuit simulator but that are necessary for optical circuits. The necessary parameters for simulating optical devices are wavelength, polarization, and waveguide mode, but an electrical circuit simulator cannot handle them.

In this study, we used an equivalent circuit of an optical device in an electrical circuit simulator for photonics-electronics convergence design. Other design techniques have used equivalent circuits of optical devices in an electrical circuit simulator [5–7]. However, a conventional equivalent circuit uses several lumped elements to express only the frequency response of optical devices. It cannot use device structures or physical parameters as calculation parameters. Thus, when an optical device is redesigned, the equivalent circuit has to be modeled again. To design an optical device in an electrical circuit simulator, the equivalent circuit should consist of lumped elements that have a one-to-one correspondence with the structural components and physical parameters of an actual device. This allows us to

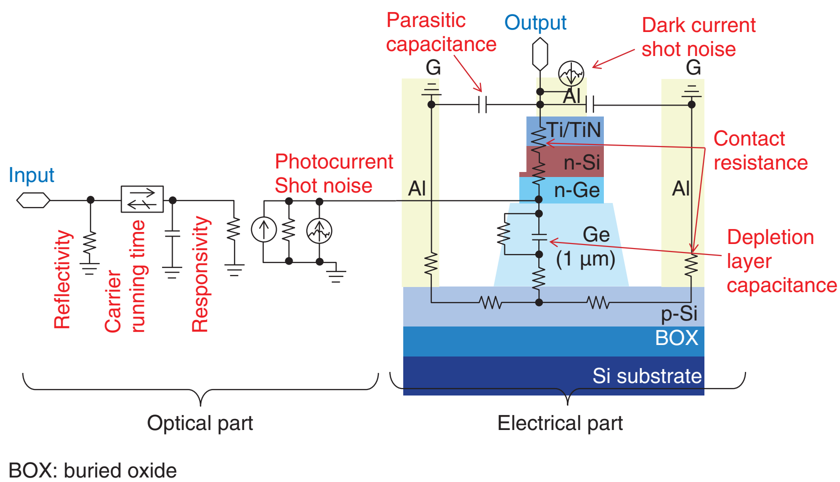



Fig. 2. Structure of Ge-PD equivalent circuit.

carry out structural and material redesigns of optical devices in an electrical circuit simulator by changing the parameters of the lumped elements.

## 2. Design of optical equivalent circuits

### 2.1 Model for designing optical devices in an electrical circuit simulator

In this study, we used a germanium photodiode (Ge-PD) for the optical device, as shown in **Fig. 2**. We used lumped elements in our equivalent circuit and divided it into electrical and optical parts. The electrical part consists of the contact resistances, the capacitance and resistance of the depletion layer, shot noise due to dark current, and the parasitic capacitance between electrodes. These parameters of the lumped elements are independent of each other and have a one-to-one correspondence with the structural components of an actual Ge-PD.

The optical part of the equivalent circuit includes the optical parameters of the Ge-PD, which are responsivity, carrier running time, shot noise due to photocurrent, and reflectivity. The shot noise due to photocurrent is a function of the input optical power. The capacitance for carrier running time models the frequency dependence due to carrier drift in a Ge layer as a simple low-pass filter. The lumped elements reflect the structure and physical parameters of the Ge-PD, and the circuit parameters depend on the dimensions and material parameters. Thus, we can achieve a simple structural design of an optical device by using this equivalent circuit.

We fabricated, characterized, and simulated Ge-PDs with the same structure as in Fig. 2 to confirm the feasibility of our equivalent circuit. The detailed structure, fabrication process, and performance of the Ge-PD are described in our previous reports [8–10]. The measured and simulated S21 parameters for Ge-PDs with a heavily or lightly p-doped Si layer are plotted in **Fig. 3(b)**. The doping concentration of Si determines the contact and p-doped Si resistance as shown in **Fig. 3(a)**, which mainly determines the total resistance of the Ge-PD. In the measurement, the Ge-PD with the lightly doped Si layer shows a lower 3-dB cutoff frequency than that with the heavily doped one, as shown in Fig. 3(b). In the simulation, we changed the parameters of the two resistances, whose values were estimated from a test element group. As shown in Fig. 3, the agreement between the simulated and measured frequency responses of the Ge-PD is very good, which means that we can design optical devices by changing the parameters of the lumped elements.

### 2.2 Model for handling unique parameters of optical devices in an electrical circuit simulator

In this study, we used as an example the wavelength characteristic of optical devices. The method for handling wavelength in the electrical circuit simulator, in this case for a wavelength filter, is shown in **Fig. 4**. Details of the wavelength filter are described in our previous paper [9]. A modulated optical signal can be considered to be a modulation signal with a very high carrier frequency. In the conventional method, the carrier frequency, which is about 193 THz, is ignored

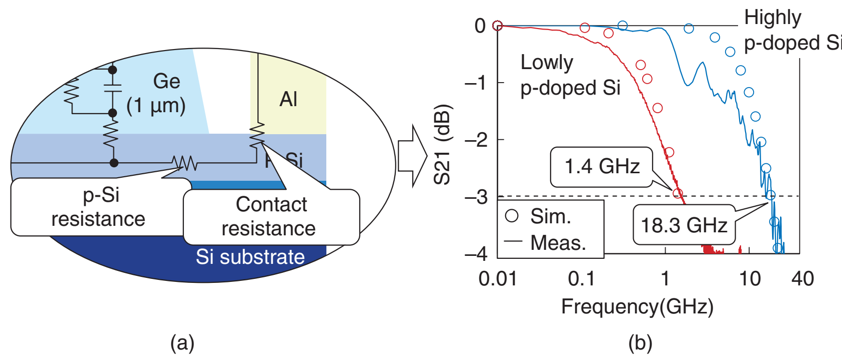
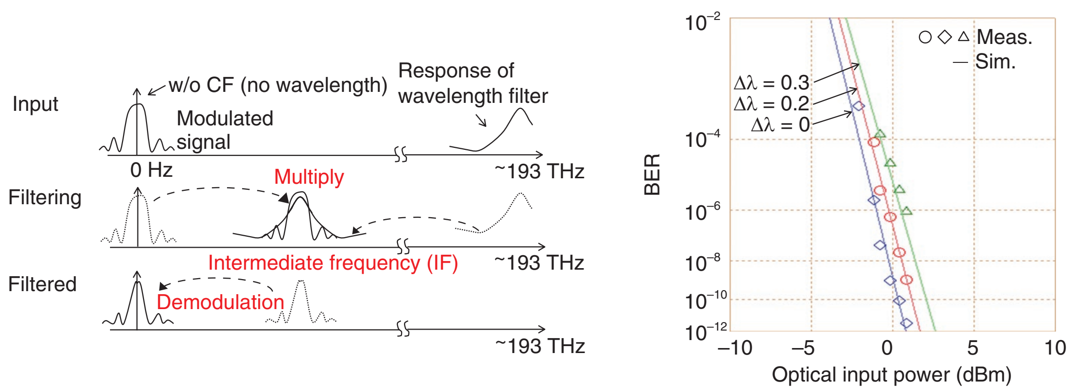



Fig. 3. Example of changing parameters using Ge-PD equivalent circuit.




(a) Signal processing with IF to handle wavelength in electrical circuit simulator

(b) Measured and simulated BERs

CF: carrier frequency

Fig. 4. Method for handling wavelength in electrical circuit simulator.

because it is too high for an electrical circuit simulator to handle. In this study, we down-converted the carrier frequency and the frequency response to an intermediate frequency (IF). We use the IF as a pseudo-carrier frequency to indicate the wavelength dependence in an optical device. The signal processing with an IF to handle wavelength in an electrical circuit simulator is shown in Fig. 4(a). An input signal is multiplied by the IF, and the center frequency of the wavelength filter is down-converted to it. Optical signal processing such as filtering and phase modulation is performed around the IF. Finally, the carrier frequency is removed, and the envelope signal is extracted.

The measured and calculated bit error rates (BERs) of a signal after it has passed through a wavelength filter are shown in Fig. 4(b). Here, Δλ is defined as the difference between the IF and the center frequency of the ring resonator response. The pseudo-random bit sequence (PRBS) transmission word length and data rate were $2^{31}$–1 and 12 Gbit/s. As Δλ increases, the BERs shift to the high input power side because the input signal should compensate for a power penalty due to the wavelength filter. In the calculation, the BERs agree well, with the difference being at most 1 dB. The power penalty due to the wavelength shift is properly depicted. We concluded from the simulation results that we have managed to use the IF to model the wavelength dependence in an electrical circuit simulator.

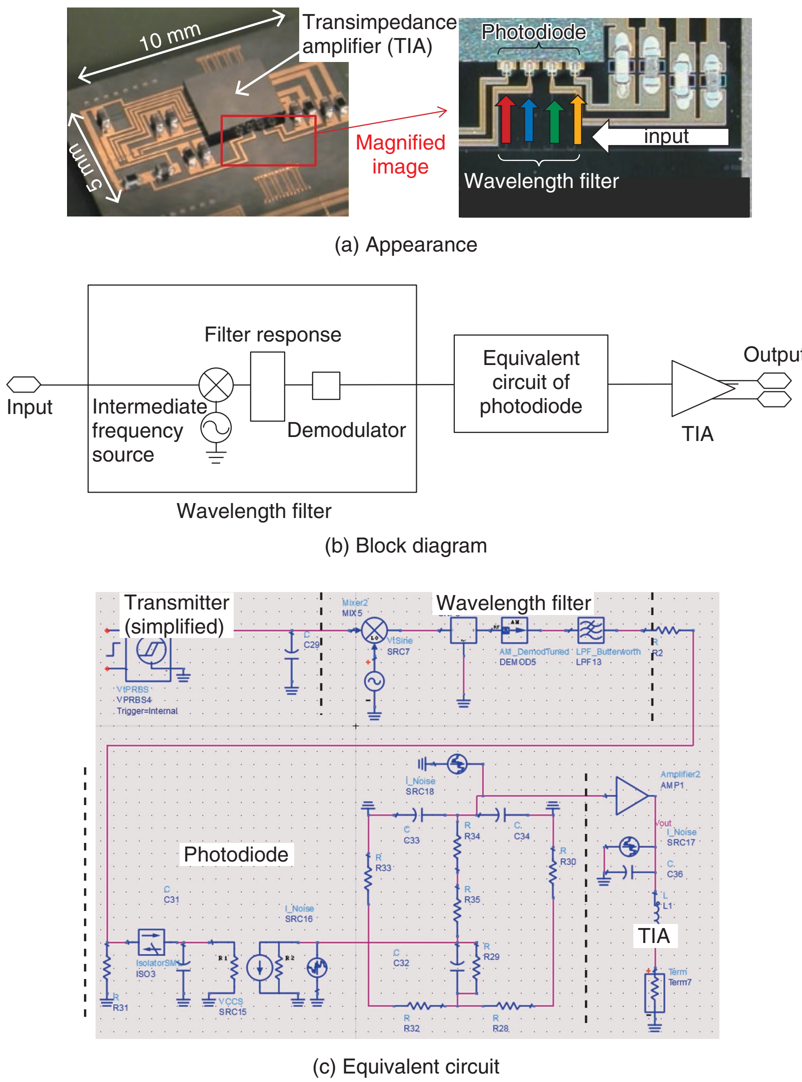
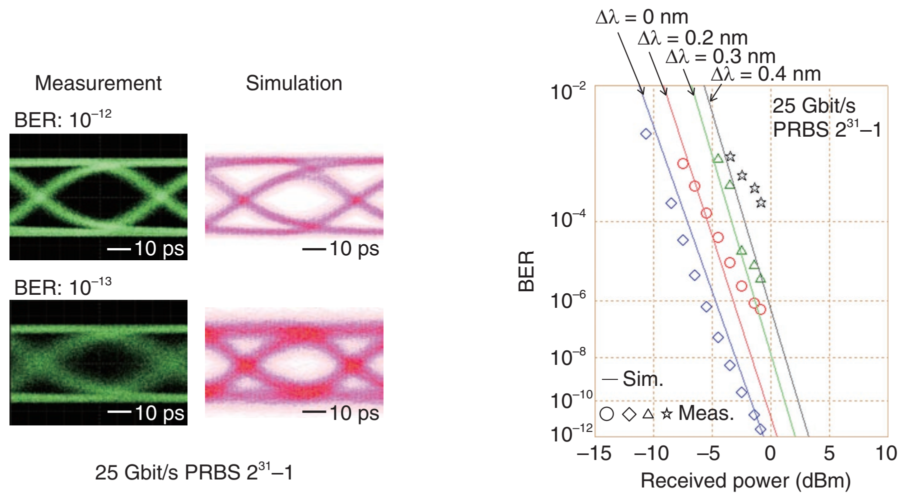



Fig. 5. Optical receiver with integrated electrical circuit.

## 3. Measurement and simulation results for optical receiver with integrated electrical circuit

We fabricated an actual silicon photonic optical receiver with our in-house transimpedance amplifier (TIA) as a test device for photonics-electronics convergence simulation, as shown in **Fig. 5**. A block diagram of the optical receiver is illustrated in Fig. 5(b). It contains a wavelength filter, a Ge-PD, and the TIA. As shown in Fig. 5(a), these devices are integrated densely on one chip. Details of the optical receiver are described in our previous papers [11, 12]. An equivalent circuit of the optical receiver is shown in Fig. 5(c). We used a simplified TIA model to reduce the computational cost. The parameters of this simplified TIA block are the frequency response, input referred noise, and transimpedance. These parameters are determined from the discrete TIA chip. The simulated and measured eye diagrams and BERs of the optical receiver for $\Delta\lambda$ = 0, 0.2, 0.3, and 0.4 nm are given in **Fig. 6**. The PRBS word length and bit rate were $2^{31}-1$ and 25 Gbit/s. The IF was set at 200 GHz. The measured and simulated BERs agree well, with an error less than 3 dB, and the simulations properly depict the power penalty due to a wavelength shift. Thus, we can conclude that we were able to successfully simulate a photonics-electronics convergence device. In other words, we can design photonics-electronics convergence devices using an electrical circuit simulator as a unified design platform.




(a) Simulated and measured eye diagrams

(b) Simulated and measured BERs

Fig. 6. Simulated and measured eye diagrams and BERs.

## 4. Summary

We developed a design technique for photonics-electronics convergence that uses equivalent circuits of optical devices in an electrical circuit simulator. The technique uses the physical parameters and dimensions of optical devices as calculation parameters. This allows us to design optical devices in an electrical circuit simulator. We also use an intermediate frequency to model the wavelength dependence of an optical device. We combined these techniques to simulate the BER and eye patterns of a Si photonics optical-electrical integrated receiver. The simulated and measured BERs and eye diagrams showed good agreement, and the power penalty due to the wavelength shift was properly depicted. This technique uses only the ordinary functions of the electrical circuit simulator. It does not require any other simulator platform. Thus, the electrical circuit simulator becomes a photonics-electronics convergence simulator by virtue of the equivalent circuit of optical devices. This is the first step to establishing a photonics-electronics convergence design for digital mock-up.

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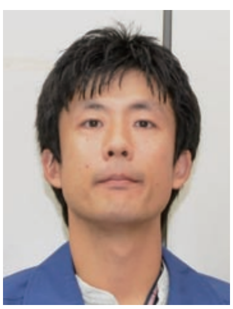

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# High-speed Optical Packet Switching for Photonic Datacenter Networks

*Toru Segawa, Yusuke Muranaka, and Ryo Takahashi*

**Abstract**

Today's large-scale datacenters have been constructed using a large number of electrical routers and switches, and they are consequently facing problems such as high power consumption, high latency, and low network throughput. Some of the research aimed at solving these problems focuses on photonic datacenters based on optical technologies. In this article, we introduce the underlying optical packet switching technologies of a hybrid optoelectronic router that researchers at NTT Device Technology Laboratories are currently working on. We also explain a high-speed optical switch, which is a key component of the router.

*Keywords: datacenter network, optical packet switching, optical switch*

## 1. Introduction

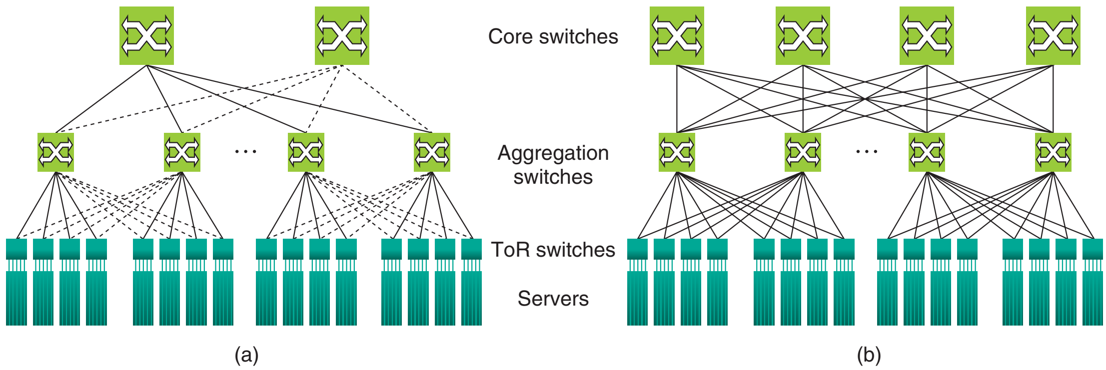
The use of datacenters (DCs) is expanding rapidly with the spread of cloud services such as SaaS (software as a service), PaaS (platform as a service), and IaaS (infrastructure as a service). DC Internet protocol traffic around the world is growing at an annual rate of 23% and is expected to reach 8.6 zettabytes (ZB, $10^{21}$ bytes) in 2018 [1]. DCs are continuing to expand in scale and are facing problems such as large power consumption of the huge number of servers and network equipment connecting them, high latency between servers, and insufficient throughput of the network.

Efforts are underway to alleviate these problems, and these efforts include implementing changes in DC networks. Conventional DC networks have a large number of electrical switches and routers that are connected in a fat-tree hierarchical architecture, as shown in **Fig. 1(a)**. The spanning tree protocol (STP) used in these networks prevents multiple paths from being set between an aggregation switch and core switches. Such networks are powerful in handling client-server (north-south) traffic but have difficulty coping with server-server (east-west) traffic due to limited throughput, lack of scalability and flexibility, high latency, and serious power issues. As a result, DC networks have evolved from the traditional fat-tree to fabric networks [2] as shown in **Fig. 1(b)**. In this type of network, the STP is not used, and it is possible to have multiple paths between aggregation switches and core switches by using a layer 3 protocol. This has improved the network throughput by distributing the load by load balancing. However, some problems still remain such as the huge power consumption due to the large amount of network equipment, the need for extensive and complex wiring, and the limited network scalability. Research in the field of photonic DCs based on optical switching technology is actively being done in order to solve these problems.

In this article, we present current research trends in photonic DCs. We also introduce a new DC network with a multidimensional torus topology that combines hybrid optoelectronic routers (HOPRs) and an OpenFlow controller. Finally, we highlight the high-speed optical switches that are one of the HOPR's key enablers used for forwarding incoming packets on a packet-by-packet basis.

## 2. Expectations for photonic DCs

Optical switching technologies used in photonic networks can be divided into optical circuit switching




EPS: electrical packet switching
OCS: optical circuit switching
OPS: optical packet switching
ToR: top of rack

Fig. 1. Configuration of (a) traditional fat-tree DC network and (b) recent fabric DC network.

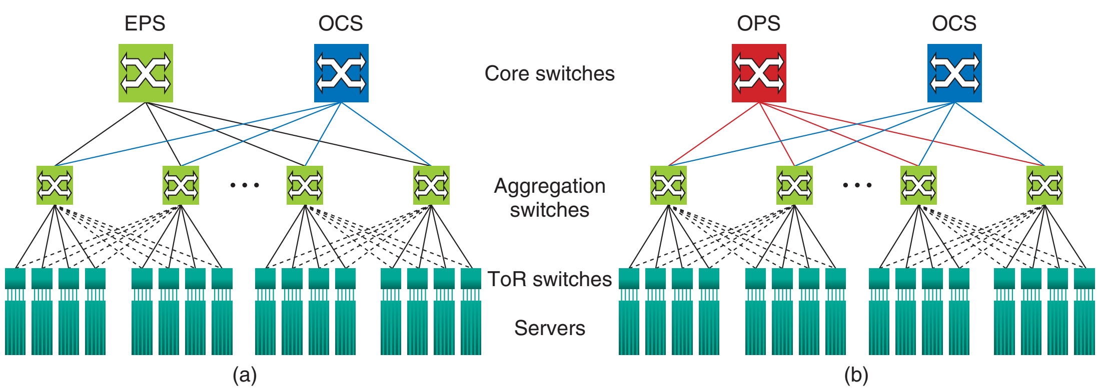



Fig. 2. Photonic DC networks: (a) EPS/OCS and (b) OPS/OCS.

(OCS), optical burst switching (OBS), and optical packet switching (OPS), depending on data granularity. OPS is promising for small-data transmission where data are forwarded on a packet-by-packet basis with low latency and high power efficiency, although the possibility of packet loss is not completely avoidable. OPS is also capable of coping with large traffic fluctuations while maximizing the bandwidth utilization, as a number of optical packets with different destinations can be multiplexed in one wavelength band, which is known as statistical multiplexing. OCS is suitable for large-capacity transmission because it provides reliable links with constant latency and without packet loss. However, it is not suitable for networks in which quick changes occur in the demanded connection paths, as it requires a long setting time to establish a dedicated path at a given wavelength.

The amount of research being done on photonic DC networks based on such OCS/OPS technology has recently increased. For example, a network that combines conventional electrical packet switching (EPS) and OCS has been proposed, as shown in **Fig. 2(a)** [3]. In this network, large-capacity data are forwarded by OCS, making it possible to reduce the end-to-end latency after the links are established and to improve the network throughput by offloading the EPS traffic. Introducing OPS instead of EPS, on the other hand, makes it possible to reduce the latency substantially, even though the paths may be longer compared to OCS, because no time is needed to establish links. Other advantages include reduced power consumption

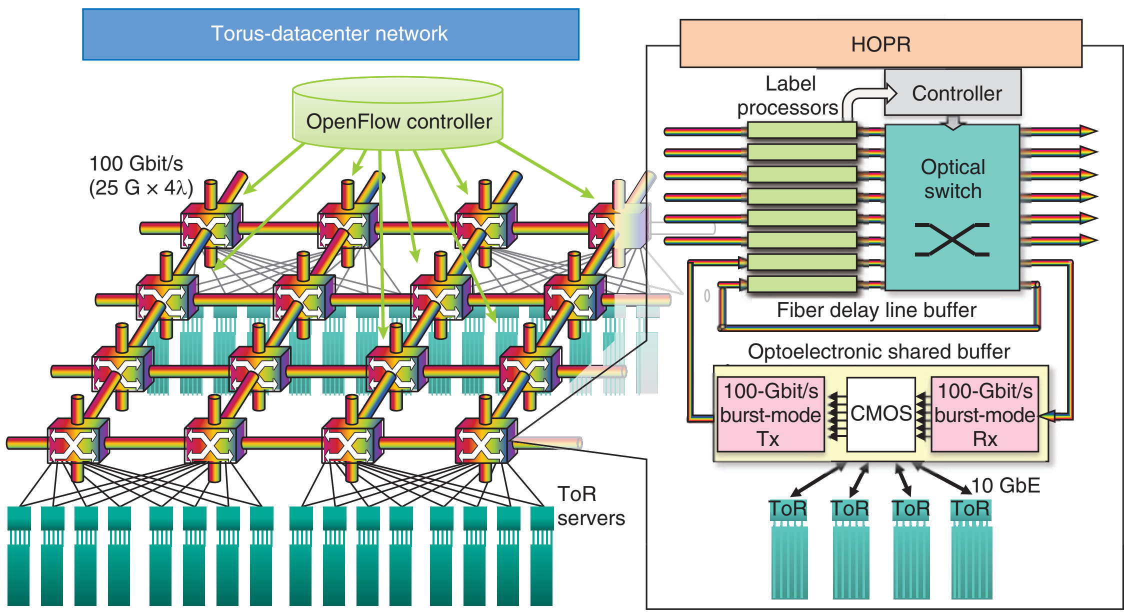



Fig. 3. Architecture of proposed torus-datacenter network with HOPR.

and improved network throughput. For example, a network with a hybrid OPS/OCS configuration has been proposed, as shown in **Fig. 2(b)** [4]. However, such a hybrid EPS/OCS or OPS/OCS configuration requires separate hardware platforms with different sets of controls.

We have proposed a DC network with a torus topology based on the combination of HOPRs and an OpenFlow controller, as shown in **Fig. 3**. The new flat network provides robust redundancy and superior scalability. In addition, the combination of the OpenFlow-based centralized control and the label processor-based distributed control enables OPS, OCS, and virtual OCS all on a single hardware platform to support a diversity of services in DCs [5]. The HOPR is divided into two parts; one part consists of the optical packet switch that comprises the label processors, optical switch, and optical fiber delay line, and the other part consists of the optoelectronic shared buffer. The HOPR forwards burst-mode 100 Gbit/s (25 Gbit/s × 4λ) optical packets as they are in the optical domain, that is, without performing optical to electrical conversion. However, it is difficult to process such high-speed burst-mode optical packets with the commercially available components and equipment. Therefore, we are developing novel optical and optoelectronic devices in our labs in order to construct a new HOPR prototype that can handle 100-Gbit/s burst-mode optical packets.

## 3. High-speed optical switch technology

One of the key devices in the HOPR is an N×N optical switch that is used for forwarding the incoming optical packets to their desired output ports. Because the data rate of the optical packets is 100 Gbit/s, the length of ordinary Ethernet packets that need to be forwarded is as small as 120 ns. Thus, it is essential to be able to perform switching at a higher speed within the guard bands, that is, the time separating successive packets, which are at least an order of magnitude shorter than the packet length. In addition, the switch needs to be insensitive to bit rate (10–400 Gbit/s), packet format (coherent, wavelength division multiplexing (WDM)), wavelength, and polarization, besides fulfilling other basic demands such as low power consumption, high extinction ratio, low crosstalk, ease of controllability, and compactness. To meet these requirements, various optical switches have been demonstrated so far such as the matrix switches achieved by cascading 1×2 switches, phased-array optical switches, wavelength-routing switches, and broadcast-and-select switches.

Of these switches, we consider the wavelength-routing switches and broadcast-and-select switches to be the most promising. The structures of these

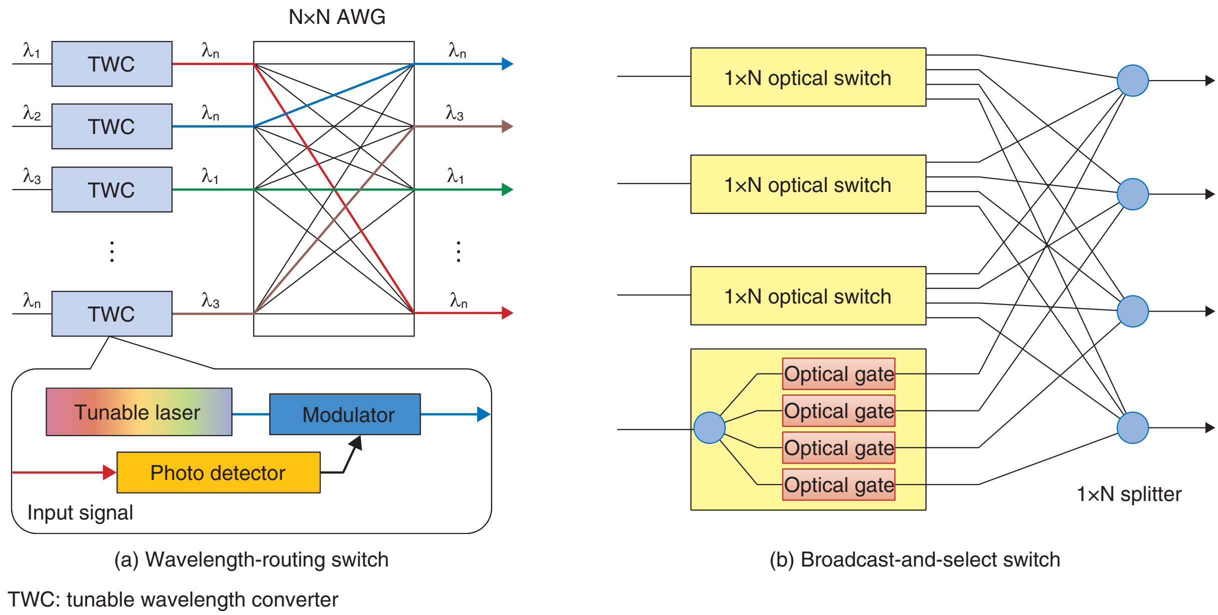



Fig. 4. Schematic configuration of wavelength-routing switch and broadcast-and-select switch.

switches are shown in **Fig. 4**. The wavelength-routing switch consists of a tunable wavelength converter that changes the wavelength of the input signal light, and an N×N arrayed-waveguide grating (AWG). Since the output port of the N×N AWG is determined by the input wavelength, the AWG enables the input packet to be forwarded to a given output port by converting the packet wavelength to the desired wavelength with a tunable wavelength converter. This kind of optical switch is characterized by high scalability, as it is possible to increase the number of ports N by making the wavelength-channel spacing narrower, without increasing the AWG losses.

The broadcast-and-select switch, on the other hand, is an optical switch that consists of a 1×N optical splitter and optical gates. The input signal is equally divided by a 1×N optical splitter. Optical switching is done by blocking the light or allowing it to pass using the optical gate attached to the desired output port. This optical switch suffers from limited scalability, though, as the splitting losses increase with the increase in the number of switch ports. It also operates with a simple control for blocking or unblocking the optical gates. Thus, both the wavelength-routing and broadcast-and-select switches have their own merits, and we are conducting research on both of these optical switches.

We have proposed a tunable transmitter that relies on a semiconductor ring resonator [6]. A photo of this device is shown in **Fig. 5**. This device has a tunable laser and optical modulator integrated on a single chip. The tunable laser is promising as a high-speed tunable light source where a low driving current is necessary to change the output wavelength. Moreover, it can suppress the gradual drift in lasing wavelength caused by the Joule heating effect with current injection. The tunable laser employs ring resonators placed in parallel as a wavelength filter for selecting the lasing wavelength and as a loop mirror that forms the laser cavity. With this configuration, it is possible to improve the wavelength selectivity while increasing and stabilizing the optical output. The optical modulator is an electro-absorption modulator (EAM) with InGaAlAs (indium gallium aluminum arsenic)-based multiple quantum wells; it enables operation with a high extinction ratio over a wide range of wavelengths. Using this device and an AWG with 100-GHz channel spacing, we demonstrated error-free wavelength-routed switching for 25-Gbit/s burst-mode optical packets [6].

We have also proposed a broadcast-and-select switch based on monolithically integrated EAM gates [7, 8]. A two-array device of 1×8 optical switches is shown in **Fig. 6**. To compensate for splitting/coupling loss, semiconductor optical amplifiers (SOAs) are usually deployed as optical gates in the broadcast-and-select switches. However, SOAs characteristically experience nonlinear optical effects such as

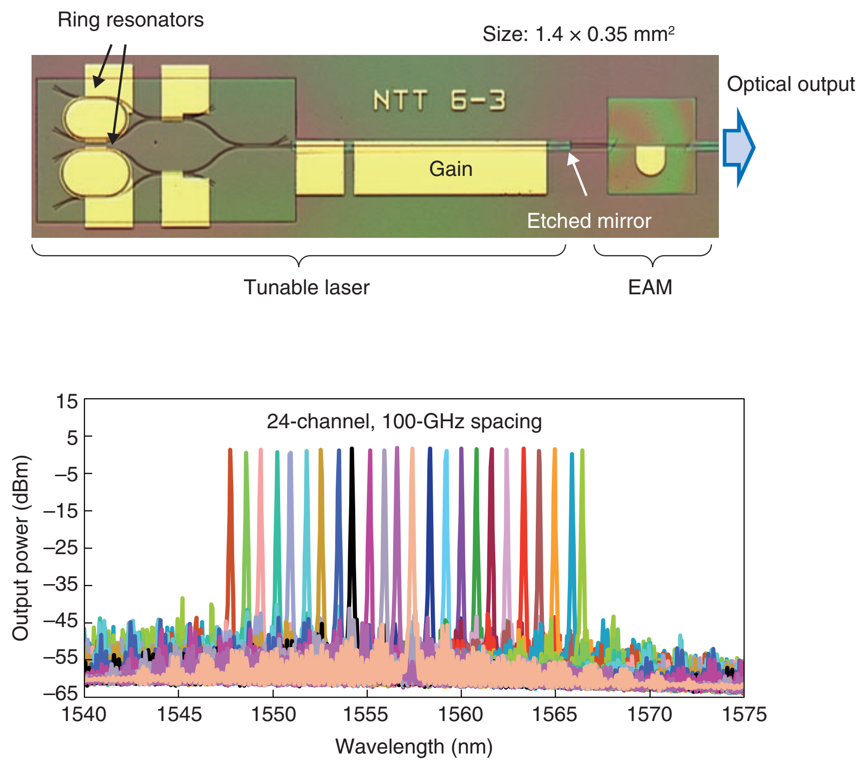



Fig. 5. Photo of tunable transmitter and output spectrum of the transmitter.

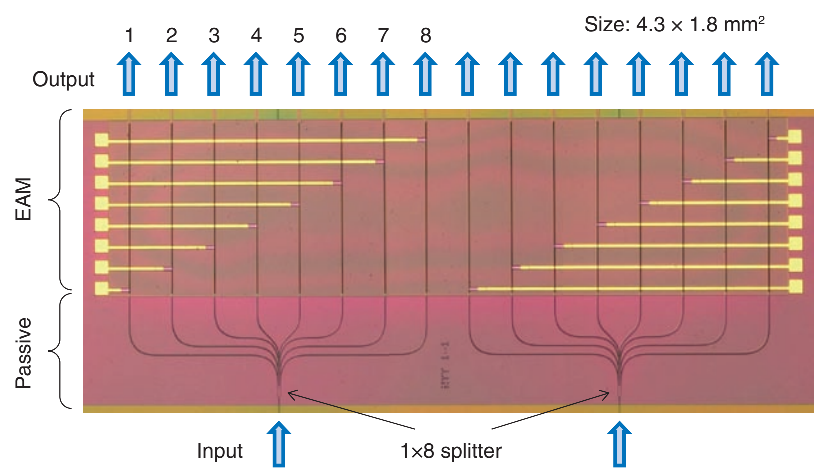



Fig. 6. Photo of two-array 1×8 EAM-gate switches.

four-wave mixing and cross-gain modulation, and signal-quality degradation for WDM signals is also an issue. An SOA also requires an electrical current of several hundred milliamperes for its operation, which necessitates a driver circuit with high power consumption. Since our alternative choice of an EAM is free from any associated nonlinear effects, and because the device in this case also operates with low current, the power consumption of the driver circuit can be reduced to an extremely low level. The EAM-based switch operates with a normally-on state. Thus, without applying any control signals, the optical

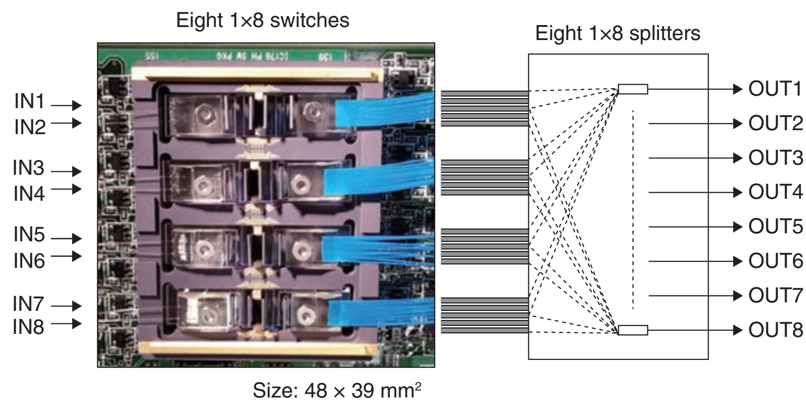



Fig. 7. Schematic of 8×8 broadcast-and-select optical switch with photograph of the fabricated module.

signal will go through the bulk active layer that is transparent and polarization-insensitive for a wide range of wavelengths even with a large change in device temperature. In contrast, the SOA-based switch operates with a normally-off state and relies on carrier injection to achieve the on-state necessary for signal transmission. The SOA gain-profile strongly depends on the energy distribution of carriers, which causes its performance to exhibit undesirable changes with wavelength, polarization, or temperature. Thus, in terms of wavelength dependent loss (WDL), polarization dependent loss (PDL), and temperature dependent loss (TDL), the EAM-based switch provides clear advantages when compared to the SOA-based counterpart.

Our fabricated switch module exhibited a small WDL and PDL of typically ± 0.5 dB in the wavelength range of 1540–1560 nm [7, 8]. We have developed a compact 8×8 broadcast-and-select switch module that accommodates eight 1×8 optical switches, as shown in **Fig. 7**. It exhibits superior properties such as a switching time of no more than 10 ns, a high extinction ratio of at least 40 dB, and power consumption of 3 W or less. We have also achieved error-free forwarding for 25-Gbit/s optical packet signals [9]. This device has excellent low-power, high-speed, and broadband capabilities and is very promising as an optical switch for forwarding large-capacity optical packets since it is compatible with various optical signal formats.

## 4. Future work

We are currently considering scaling-up the high-speed optical switches (e.g., up to 16×16), and we are also fabricating a pre-prototype HOPR that combines the three basic functionalities of optical label processing, optical switching, and optical buffering. In the future, we plan to build and demonstrate a DC network with a torus topology using the pre-prototype under development, and we will continue our research efforts aimed at realizing environmentally friendly DC networks.

## Acknowledgment

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# Hardware/Software Co-design Technology for Network Virtualization

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**Abstract**

Network virtualization technology is a topic of great interest because of its ability to emulate network features in software. In this article, we present a technique for adding programmable hardware acceleration to network virtualization equipment, which is then used in coordination with software to preserve the software's flexibility while raising the limits on its performance.

*Keywords: network virtualization, convergence of software and hardware, FPGA (field-programmable gate array)*

## 1. Introduction

As the performance of commodity servers has improved, we have set out to rapidly provide services with reduced operating and capital expenditures by employing network virtualization technology. Software-defined networking (SDN) is representative of this; it separates the features that control a communication device from the device's data transfer functionality, enabling network configurations and settings to be centralized in and automatically controlled by software. To apply this SDN technology to carriers' wide area networks, NTT has taken the lead in the accelerated research, development, and open-source release of an SDN application to the world. Our application has two components: the Ryu SDN Framework [1] and Lagopus [2]. The Ryu SDN Framework is an SDN controller that provides convenient tools and libraries for easily setting up an SDN. Lagopus is a high-performance SDN software switch with capabilities and features that have broad applications from datacenters to wide area networks.

## 2. Development of hardware accelerator for network virtualization

Network features that have traditionally been provided by dedicated hardware can now be implemented in software by network virtualization technologies on commodity servers. As the use of network virtualization becomes more common, we can expect commodity servers to be equipped with many network features that will increase the load on the servers' central processing units (CPUs), which will be responsible for handling network-related processing. If we want to meet the demands for even more advanced network services and systems, we will need technology that can alleviate this additional CPU load in order to increase the power/performance ratio of processing on commodity servers and thus provide a stable environment for running more software.

The NTT Device Innovation Center has been involved in researching and developing hardware/software co-design technologies to help hardware and software work together. We developed a hardware accelerator (HWA) [3, 4] that implements the concepts shown in **Fig. 1**, improving performance and reliability while preserving the flexibility of the highest-performance SDN software switch in the world, Lagopus.

## 3. HWA properties

The system configuration of an SDN software

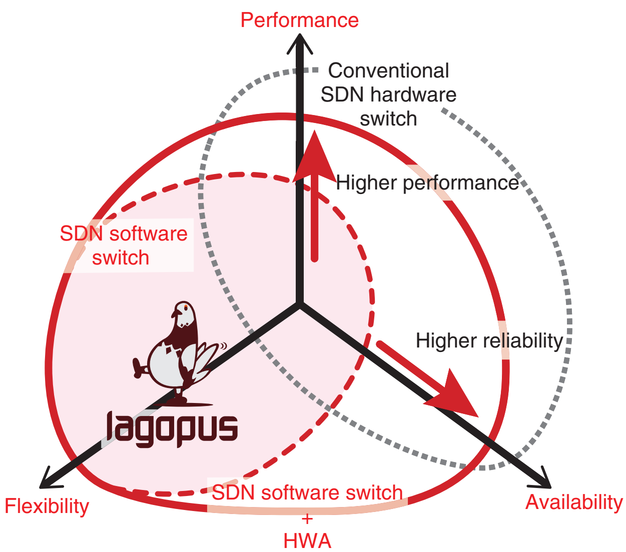


Fig. 1. Conceptual diagram of hardware accelerator.

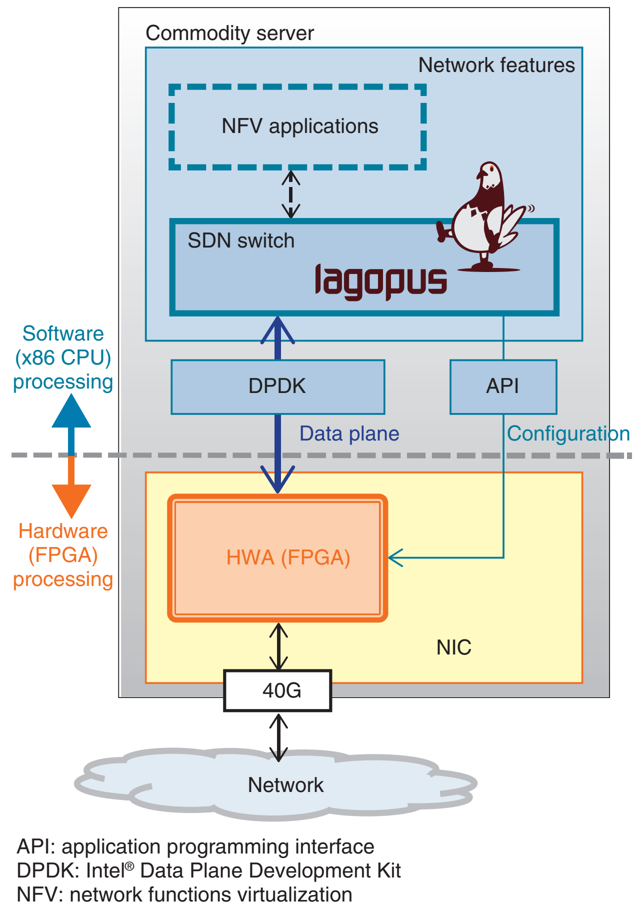


Fig. 2. System configuration for SDN software switch.

switch with the HWA we developed is shown in **Fig. 2**. The system is characterized by a reconfigurable HWA—specifically, a field-programmable gate array (FPGA)—placed on a commodity server's network interface card (NIC). Hardware ordinarily takes much longer to develop than software. However, by using an FPGA, which can be overwritten with features implemented in a program, we can not only speed up the development process, but we can also update network features and quickly make changes to fix problems that arise later.

The SDN software switch system in Fig. 2 forwards network packets through the FPGA on the NIC to the software that will process them. In addition to the NIC's ordinary packet processing, the FPGA has implemented preprocessing features to assist with the first part of the heavy processing in Lagopus's packet forwarding component (i.e., the data plane). The HWA's preprocessing cannot directly communicate with—and is independent of—Lagopus's packet processing. This allows Lagopus to retain its flexibility while reducing the software load and further improving the performance of the SDN software switch. Specifically, we have developed the following three features.

(1) High-speed flow dispatcher

High-speed packet processing on a software switch requires evenly distributing the work among the processing units (cores) in a multi-core processor (CPU), which can process multiple instructions in parallel. There usually is no mechanism for distributing the packet load in advance, so packets must be sent to a designated CPU core to be divvied up in software. This could cause packets to pile up on a single CPU core, creating a bottleneck, and in the worst-case scenario leading to packet loss. The high-speed flow dispatcher feature assigns packets to FPGA data structures (queues) based on the packet flow data received by the hardware, as shown in **Fig. 3**. Direct memory access (DMA) is then used to transfer packets to the main memory regions used by the CPU cores. In this way, the total processing load is distributed and smoothed out across all CPU cores without wasting software cycles.

(2) Flow director

In conjunction with the high-speed flow dispatcher feature, we need a way for software to freely specify which flows to assign along with their corresponding DMA queues. The flow director feature allows Lagopus to accomplish this by communicating with the

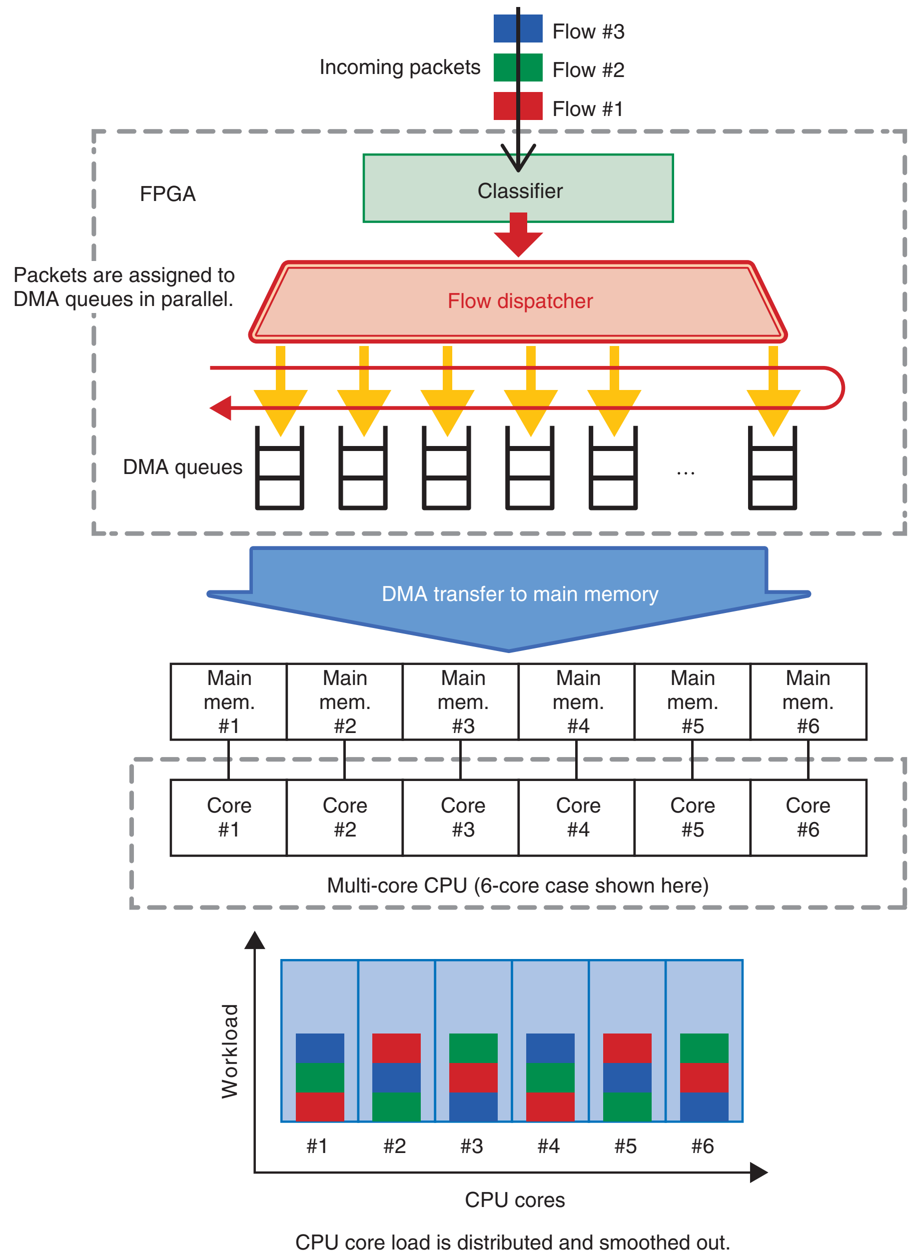


Fig. 3. High-speed flow dispatcher.

hardware through an application programming interface (API). The flow director feature can be used to improve performance. Lagopus can figure out how flows should be assigned to CPU cores, so flows do not need to be identified twice, and the corresponding processing can be skipped (**Fig. 4**). This gives Lagopus enough spare time to process short packets more efficiently.

(3) Packet mirroring

We will need to make it easier to track down the cause of network problems in the future because we expect them to become more complex with advances in network virtualization. To that end, we have implemented packet mirroring in our HWA, enabling virtual networks to be monitored at all times without placing any burden on the software. This feature copies incoming packets within the FPGA and forwards

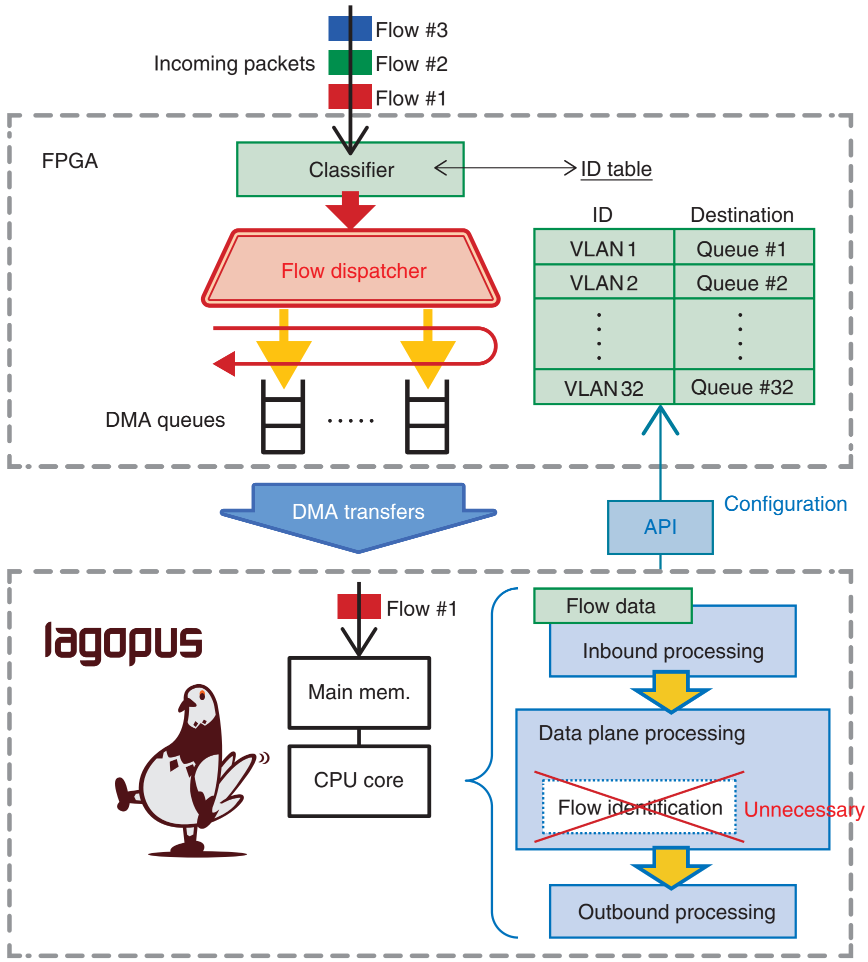


Fig. 4. Flow director.

them unmodified to an external device for analysis (**Fig. 5**). Problems can then be analyzed, and signs of possible problems can be detected without affecting normal packet processing.

## 4. Trial and evaluation of systems with hardware acceleration

In collaboration with Xilinx Inc., we tested a prototype of our SDN software switch system equipped with an HWA that had all of the aforementioned features. We then checked the performance gains achieved through our hardware/software co-design. Our tests used the latest FPGA devices and tools (i.e., SDNet*) capable of implementing cooperative hardware/software behavior. The results of evaluating the packet-forwarding performance are plotted in **Fig. 6(a)**, and the measured power consumption is in **Fig. 6(b)**. The data show that short packets were forwarded more quickly when hardware acceleration was enabled. Furthermore, when using eight CPU cores (the maximum), our system was able to process packets longer than 384 bytes at a wire rate of 40 Gbit/s. We observed that the HWA only used 19 W—less than 5% of the 425 W used by an entire commodity server—while processing packets at 40 Gbit/s, confirming that we can achieve this wire rate with only a modest increase in power consumption. By using Lagopus to switch the HWA's packet copying feature

* SDNet (Software Defined Specification Environment for Networking): Xilinx's design tool for packet processing.

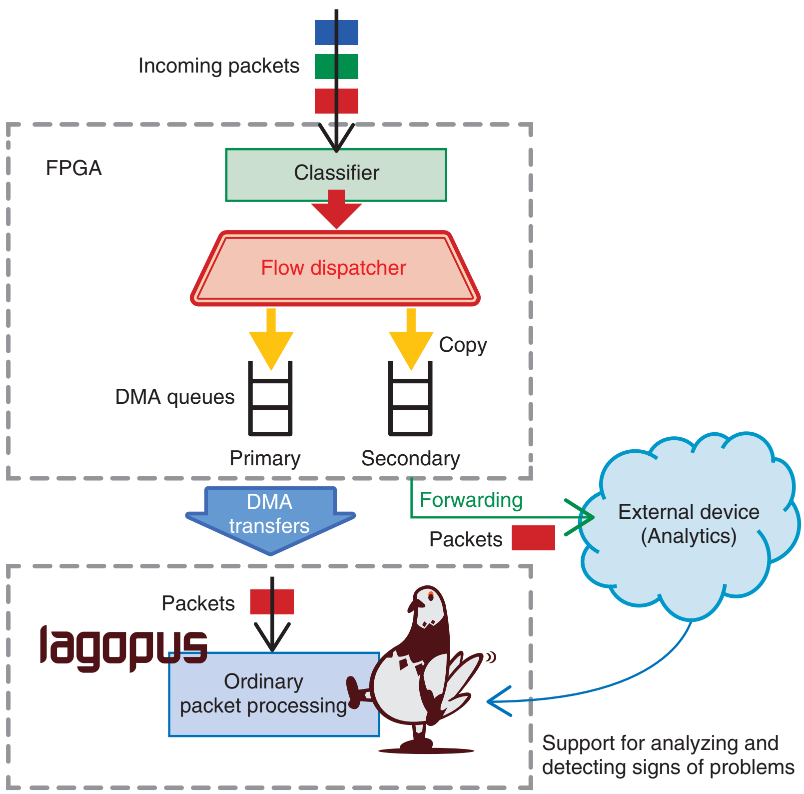


Fig. 5. Packet mirroring.

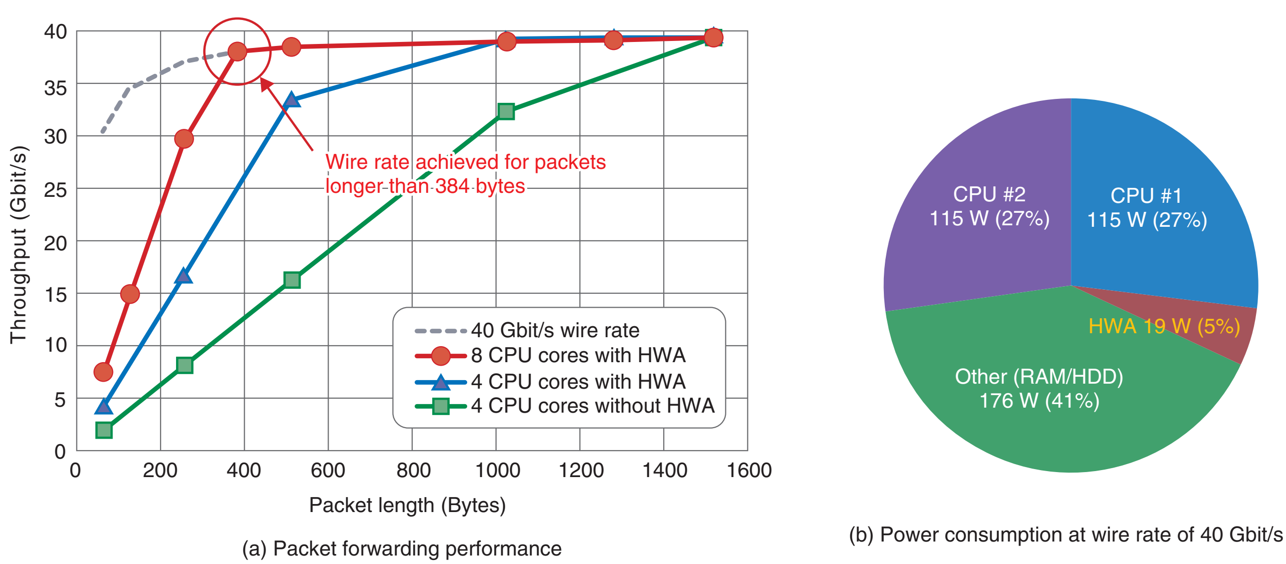


Fig. 6. Results of prototype performance tests.

on and off via its API, we also confirmed that the feature did not affect primary packet processing in our prototype.

## 5. Future plans

In the future, we will work on improving efficiency even further by tackling the problem of accepting and processing packets shorter than 384 bytes at the full wire rate of 40 Gbit/s. To further improve reliability, we will experiment with the use of packet mirroring to implement network monitoring and analysis features and thus help improve the operational aspects of network virtualization. We also plan to actually implement network functions virtualization (NFV) applications with all of these features and develop a system for trial use.

In this way, we will continue to improve the performance and reliability of our network virtualization technology, establish hardware/software co-design as a fundamental technique for network virtualization, and commercialize our technology for practical use on carrier networks.

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# Body-mind Sonification to Improve Players Actions in Sports

*Toshitaka Kimura, Takemi Mochida, Tetsuya Ijiri, and Makio Kashino*

## Abstract

It is essential that we recognize both our own physical movements and mental condition if we are to achieve and improve goal-directed actions in sports. However, it is not easy to adequately understand one's own body-mind state during complicated sports actions. A potentially better way to overcome this problem is to use auditory feedback because auditory perception has higher temporal resolution than visual perception, and it interferes very little with the performance of an action. In this article, we propose real-time auditory feedback techniques designed to sonify the temporal coordination of the body and the excessive activation caused by mental pressure when participating in sports based on surface electromyography and acceleration signals. Our aim was to determine *when* and *how* the body-mind behaves. We believe that these techniques will help players learn the skill needed for a desired action and will reveal a player's physical and mental condition when playing sports.

*Keywords: auditory feedback, real time, motor learning*

## 1. Introduction

It is essential that we understand our own movement if we are to achieve and improve goal-directed actions in sports. However, it is not easy to adequately recognize the state of one's own body during complicated movements involving multiple segments of the body, as when a golfer needs to coordinate various movements of the arms, trunk, and legs quickly and correctly when hitting a tee shot. In addition, the body is affected by a person's mental condition; that is, the body and mind are not independent but are closely linked. Even a highly skilled player may not perform well under mental pressure. Therefore, it is very important to understand one's own *body-mind* state during sports actions so as to perform satisfactorily in an actual sports game.

NTT has long researched the neural mechanisms behind motor control, sensory perception, and emotional processing in humans. We have incorporated these findings and know-how into feedback techniques designed to convey certain key features of the body-mind state during actual sports actions. Specifically, we propose using auditory feedback to obtain the temporal structure of segmental motions and muscle activity using synthetic sound. Our aim is to make a player intuitively aware of when and how his/her body-mind behaves.

## 2. Use of auditory feedback

To sense one's own motor state (e.g., posture, motion, and muscle activity) during ongoing movement, we mainly depend on proprioception, which originates in the sensors in muscles and joints. However, proprioception offers only rough spatiotemporal resolution. Thus, many studies have proposed various ways of providing the motor state with a multimodal approach based on, for example, vision, audition, or haptics, to compensate for poor proprioceptive information [1]. Visual feedback has been the most widely used way of displaying body motion (e.g., looking at snapshots and video). However, visual feedback is also assumed to have some limitations. First, we cannot fully use vision during an ongoing action because vision is commonly used for other goals (e.g., looking at a target). Furthermore, vision is expected to be limited in terms of showing the temporal structure of segmental activities because of the insufficient temporal resolution of human visual perception, even though the very quick coordination of multiple body segments is a key feature in some sports.

A potentially better way to overcome the above problems is to use auditory feedback. One reason for this is that unlike vision, human auditory perception is much less likely to interfere with performing an action, which is a benefit of providing feedback in real time. Auditory perception also has higher temporal resolution than vision. In fact, human beings often utilize auditory feedback to understand the temporal structure of motor behavior in daily life. A very familiar example is speech articulation. It is well known that speech articulators (e.g., the lips and tongue) have a very quick and complicated pattern, and auditory feedback plays a crucial role in controlling speech articulation [2]. We designed techniques for real-time sonification of the body-mind state to extend the human auditory system so that it can utilize motor control in the body in addition to speech.

## 3. Sonification of sports action

Although previous studies have already applied auditory feedback to sports, most of them have sonified behavioral outcomes (e.g., ski displacement [3]) or individual segmental activities (e.g., the timing of wrist and ankle movements in karate [4]). However, these kinds of feedback for individual outcomes and activities may be insufficient to utilize for motor recognition and learning because the spatiotemporal coordination of the body appears to be critical in terms of achieving a skillful movement in most sports. In contrast, our idea is to sonify body coordination, namely when and how a player controls his/her body, based on muscle activity and acceleration signals in multiple target segments. We expect our artificially provided auditory feedback to be integrated with original proprioceptive information during sports actions and that this integration will facilitate improvements in sports skills.

### 3.1 Sonifying segmental coordination

For most sports, it is critical to coordinate multiple body segments sequentially. For instance, when pitching a baseball, a pitcher needs to operate his/her body segments in sequence from the leg to the arm, which is a well-known segmental kinetic chain [5], and a novice pitcher cannot perform this sequence well. Thus, we attempted to sonify such sequential patterns during pitching using acceleration signals recorded on the pitcher's trunk, and then to apply it to pitching practice for novice participants.

An example of the sonification of the pitching sequence of the trunk in a single novice participant is shown in **Fig. 1**. We attached wireless acceleration sensors (Trigno, Delsys) at three different positions (P1, P2, and P3) on the back of the trunk (Fig. 1(b)) and detected three axes of acceleration signals at a 300-Hz sampling rate. We used analog acceleration signals during pitching to calculate two acceleration components in real time, namely, trunk rotation (A1) and tilting (A2); we calculated A1 and A2 from the P2 minus P1 signals and P3 minus P1 signals, respectively (top two panels in Fig. 1(c)). Then a sound (S) is synthesized as

$$S(t) = A1(t)\ S1 + A2(t)\ S2, \tag{1}$$

where S1 and S2 indicate band-limited pink noise with peak frequencies of 100 and 500 Hz, respectively. The lowest panel in Fig. 1(c) shows a spectrogram of the generated synthesized sound. Although this spectrogram contains two unclear frequency components, if the player performed a good trunk motion he/she would be able to hear the two components separately (see Fig. 1(d)). Time 0 approximately indicates the ball release timing of pitching.

The above sonification (auditory feedback) was applied while two novice participants engaged in pitching practice that consisted of repeating 100 non-dominant arm pitches with a fixed step length and moderate effort (Fig. 1(a)). In particular, they focused on trunk rotation and tilting, which are targeted in the feedback information, because novices frequently exhibit poor trunk motion [6]. They also performed other practice trials using visual feedback (6-sec.-delayed video streaming) in a separate session for comparison with the effect of auditory feedback. The order of auditory and visual practice sessions was counterbalanced between the two participants. At the beginning of each practice session, either the sound (Fig. 1(d)) or a video of an expert's pitch was provided as a practice target. Before and after each practice session, we measured as a test session the chest, shoulder, and wrist motions in 10 trials without any feedback using a motion capture system (Oqus 300, Qualisys).

The mean velocity waveforms of three segments (chest, shoulder, and wrist) in each test session are shown in **Fig. 2(a)** for each participant. Both auditory (AF) and visual feedback (VF) practices improved the body sequence; namely, the sequential pattern

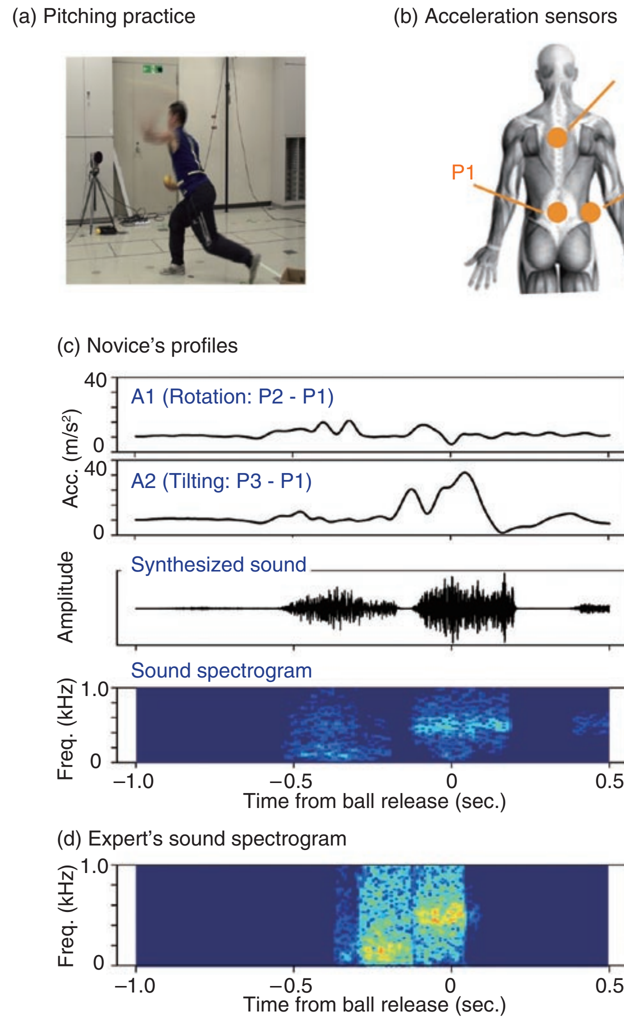


Fig. 1. Sonification of segmental coordination of the trunk during pitching.

from the chest to the wrist for peak velocity was clearer than in pre-practice trials. The inter-trial deviation of velocities for each test session is shown in **Fig. 2(b)**. Interestingly, the auditory feedback showed less velocity deviation across test trials than the visual feedback. This result suggests that our real-time sonification for segmental coordination enhances the inter-trial repeatability of movements, compared with standard visual feedback.

### 3.2 Sonifying coordination of muscle activity

The above sonification method expresses the kinematics of movement based on acceleration signals of the body. We propose here another sonification method for body state that describes the dynamics of movement, that is, the muscle activity pattern. Even if a player is made aware of a difference in motion by the sonification of kinematics, it is probably difficult to understand how to exert a force that will improve the movement because it is a theoretically ill-posed problem. Thus, we attempted to sonify the sequential muscle activity patterns, which more directly reflect the exerted force, based on multiple electromyography (EMG) signals from the trunk and the upper and lower limb muscles.

An example of the sonification of the muscle activity pattern of pitching is shown in **Fig. 3**. The generated sound consisted of multiple sound sources whose fundamental frequencies were different for every muscle and whose amplitudes were varied in proportion to the EMG activity (Fig. 3(a)). An expert (former professional) pitcher almost always exhibited

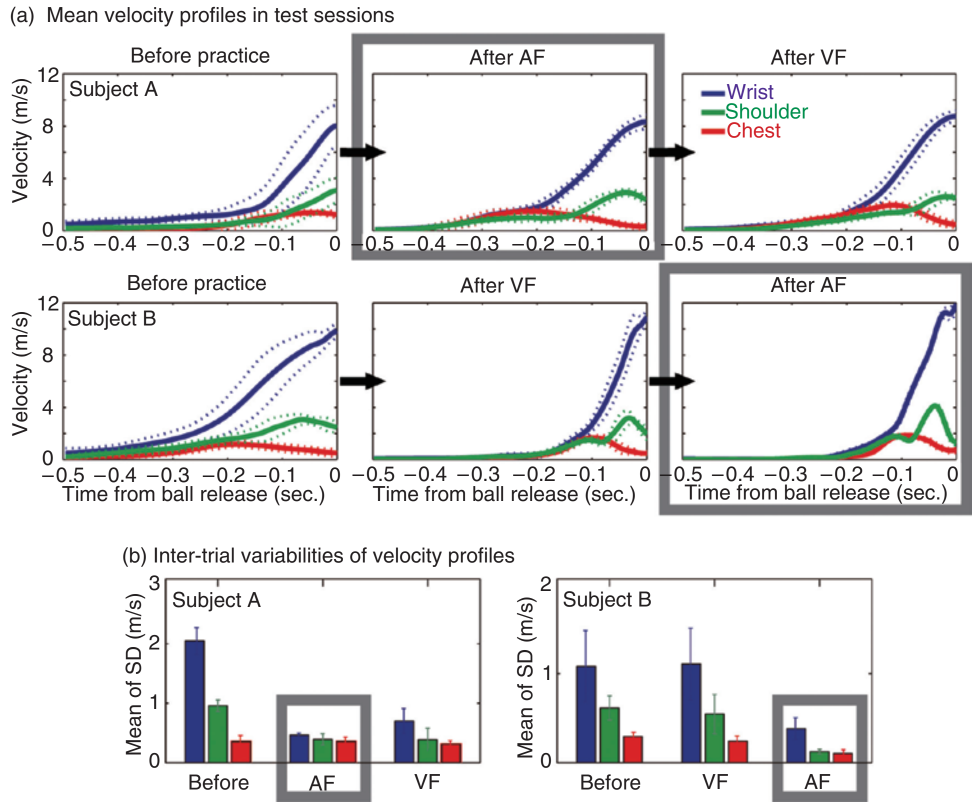


Fig. 2. Effect of sonification of segmental coordination during pitching.

a clear kinetic chain of muscle activity from the leg to the arm muscle (upper-left panel in Fig. 3(b)), while an amateur pitcher did not (lower-left panel in Fig. 3(b)), indicating unnecessary muscle activation. Therefore, the expert's sound is very rhythmical (upper-right panel in Fig. 3(b)), while the amateur's is slurred (lower-right panel in Fig. 3(b)). This sonification can be described as an *instrument* type of sonification, and a player can hear the difference in the muscle activity pattern as a melody. Using this sonification, a player can move so as to make as purposeful a sound as possible.

### 3.3 Sonification of excessive muscle activation

Some sports players cannot perform well because they try too hard, such as when putting while playing golf. This corresponds to the unintentional excessive activation of the muscles probably caused by mental pressure. That is, such excessive muscle activation reflects the state of mind. This phenomenon is very common and very serious in an actual sports match, but it is often hard to notice it. Therefore, it would be useful to make a player aware of this potential for excessive muscle activation.

An example of the sonification of overflow of muscle activity in the initial stages (address and take back) of putting in golf is shown in **Fig. 4**, based on EMG and acceleration signals of the wrist extensor muscles. The sound signal (S) consisted of a periodic waveform whose amplitude and fundamental frequency were varied in proportion to the short-term power of the EMG activity (E) divided by the acceleration (A) as follows.

$$S(t) = E(t) / A(t). \quad (2)$$

The sound mainly reflects the EMG activity when the acceleration was kept at almost zero. Therefore, the golfer could hear annoying sounds during the preparation (address) period when the muscle was activated more than necessary while the wrist moved less (lower panels in Fig. 4). Conversely, the golfer could not hear these sounds when the muscle was relaxed during preparation (upper panels in Fig. 4). Little sound was produced when the wrist was moving (take-back period) because the muscle activity and motion were coupled. This is a *warning* type of sonification, unlike the above sonification, and the

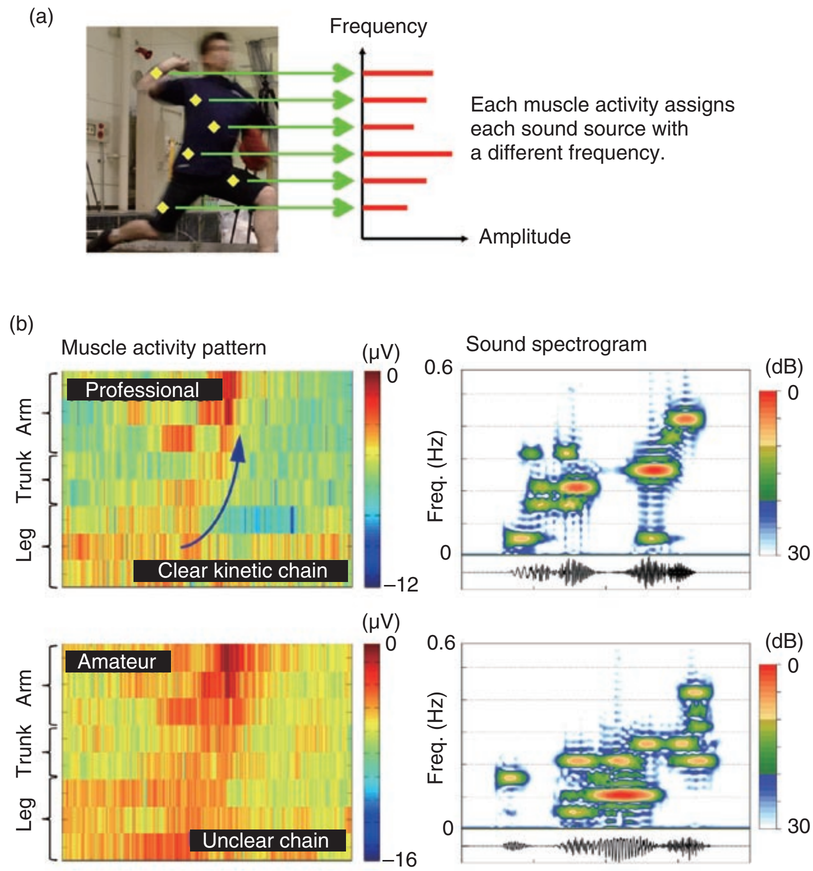


Fig. 3. Sonification of muscle activity pattern during pitching.

player aims to produce as little sound as possible.

## 4. Future developments

This article explained some novel examples of sonification of the body-mind state in sports actions. This sonification has the potential benefit of making a player aware of the coordination of movements and of his/her condition under mental pressure. However, the information regarding the body-mind state and auditory ways to provide them will vary according to the objectives and the skill level of the player. For example, the sonification of a segmental sequence (Fig. 1) would be more useful in helping a novice player to acquire the basic temporal pattern of a target action, while an instrument type of sonification of muscle activity (Fig. 3) may be more useful in helping an intermediate player to improve, rather than acquire, a given movement. Furthermore, it is likely that the sonification of excessive muscle activation (Fig. 4) is beneficial in terms of recognizing one's own mental state in an actual sports game.

We should pay attention to other elements of sonification. For instance, it is critical to determine what to provide in sonification, namely, the key essence or the *knack* of a target action, before applying our sonification. It is also important to combine it with other techniques to effectively improve a player's performance. It would be useful, for example, to combine it with visual feedback to characterize the spatial structure of an action, such as the form, while it seems more appropriate to combine it with auditory feedback to characterize the temporal structure of an action. Additionally, a wearable device such as the *hitoe* fabric bioelectrode developed by Toray and NTT would make the sonification application easy to use for players and could potentially record EMG signals during the sports action. Further research is needed to develop effective ways to enable a player to learn the skills needed for a desired action and to

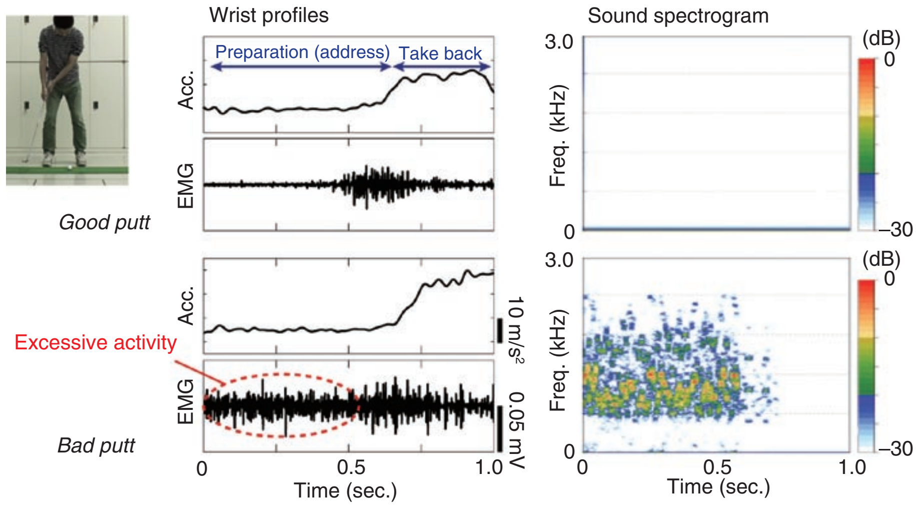


Fig. 4. Sonification of excessive muscle activation during golf putting.

reveal a player's condition when playing sports.

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# Development of Invisible Optical Fiber for Improved Aesthetic Appearance

*Keisuke Yoneda, Jun Onishi, Tetsuya Iwadou, Hironari Iino, Yoshitaka Enomoto, and Katsushi Nakayachi*

**Abstract**

When optical fiber is installed on customer premises, there may be a delay in activating it if the customer complains about the conspicuous appearance of the exposed wiring. We have developed an invisible optical fiber to improve the appearance of the installed cable and to reduce the amount of unsuccessful activation work.

*Keywords: invisible optical fiber, attachment, fixing component*

## 1. Introduction

Exposed cable is conspicuous inside and outside buildings. There may be a delay in activating the fiber if the customer dislikes the appearance of the exposed wiring. Various measures have been implemented to correct this, for example, using cable coverings. However, any covers or other components that are used must match the wall upon which the cable is installed. This can be difficult because there are various types of walls. Therefore, we have developed an inconspicuous transparent fiber with the aim of achieving a more aesthetic appearance. The structure and appearance of the fiber is suitable for various types of walls.

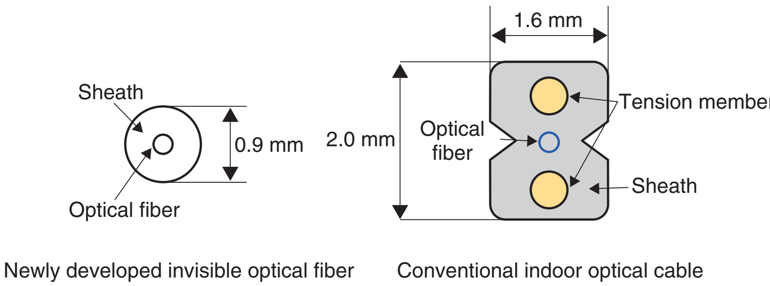
## 2. New development concept

The objective in developing the new fiber was to improve the outward appearance by using inconspicuous wiring. We aimed to develop wiring with the smallest possible diameter as well as a transparent color so that it would match any type of wall. Also, to improve the aesthetic appearance, we investigated a new distribution method using as few connection points as possible. However, the thin cable may have inferior impact resistance characteristics. Therefore, we also investigated a new installation method that uses the distribution method mentioned above along with peripheral components.

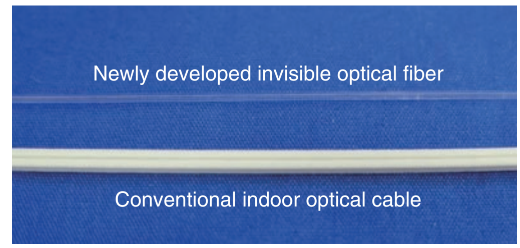
## 3. Product development

### 3.1 Invisible optical fiber

To improve the visible appearance of optical fiber cabling, we developed a transparent cable sheath instead of using the conventional black and white cable. In addition, the structure is thinner than conventional cable, with a diameter of 0.9 mm (**Fig. 1**). This product is suitable for use in restricted spaces; it can be installed in the gap around a door, for example, which is only about 2 mm wide. To install optical cable in such a small gap, we employed single-mode hole-assisted fiber (HAF) with bending-insensitive characteristics. When wiring, we use a dedicated tube in order to ensure the bending radius. The dedicated tube is also transparent (**Fig. 2**).




(a) Structure




(b) Appearance

Fig. 1. Structure and appearance of new optical fiber and conventional optical cable.

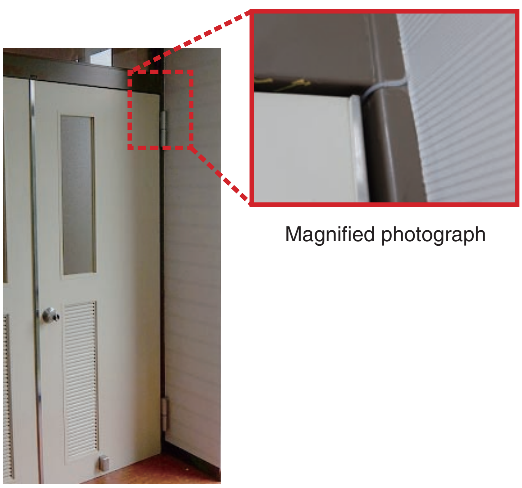



Fig. 2. Example of wiring in restricted space.

### 3.2 Connection techniques for invisible optical fiber

We developed techniques to connect the invisible optical fiber using two different materials:

(1) Fiber holder

We developed a 0.9 fiber holder to attach the field assembly connector to the invisible optical fiber. The cross-section size of the invisible optical fiber and the conventional indoor optical cable are 0.9 mm in diameter and 2.0 × 1.6 mm, respectively. Using the 0.9 fiber holder enables the invisible optical fiber to be the same cross-section size as the conventional indoor optical cable. The connector assembly procedure for an invisible optical fiber and the 0.9 fiber holder is shown in **Fig. 3**.

(2) Solid refractive index matching material

We used single-mode HAF based on ITU-T* G.657 B3 for the invisible optical fiber. A liquid refractive index matching material is used to ensure that the splicing characteristics in the field assembly connectors are sufficient. When we splice the HAF using the liquid refractive index matching material, the splice loss characteristics are degraded. This is because the matching material penetrates the air holes in the HAF, and a void is formed between the fiber end faces. This problem can be solved by using a solid refractive index matching material. Thus, we used the solid refractive index matching material with the field assembly connector for invisible optical fiber consisting of HAF. The HAF splice components with liquid and solid refractive index matching materials are illustrated in **Fig. 4**.

### 3.3 Wiring technique

The wiring route was in a corner of the wall. Cable wiring is inconspicuous when installed in the corner (**Fig. 5**). To further improve the aesthetics of the room, we used transparent fixing components. The fixing components are available as a pin-point type or protection type (**Fig. 6**), and both of these types are also sorted into two styles. The pin-point type is sorted into the simple and multi-types. The top priority with the simple type is to achieve a small size, which makes it inconspicuous. This component is fixed in place with double-sided tape. The multi-type can be fixed to different kinds of walls with double-sided tape, plaster pins, or screws. We also developed two styles for the protection type fixing components, as shown in the figure. As mentioned previously, invisible optical fiber is inferior in impact resistance because it has a smaller diameter than that of the indoor optical fiber currently used. Consequently, we

* ITU-T: International Telecommunication Union, Telecommunication Standardization Sector

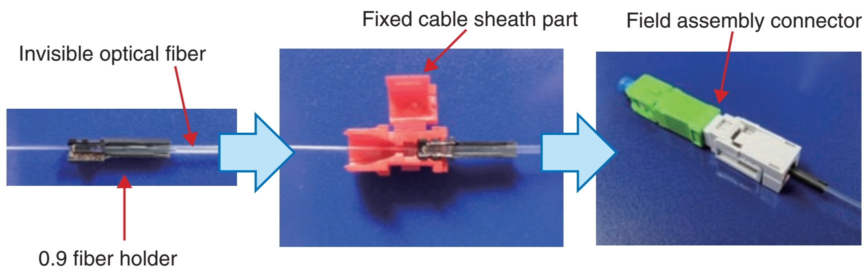



Fig. 3. Connector assembly procedure with invisible optical fiber and 0.9 fiber holder.

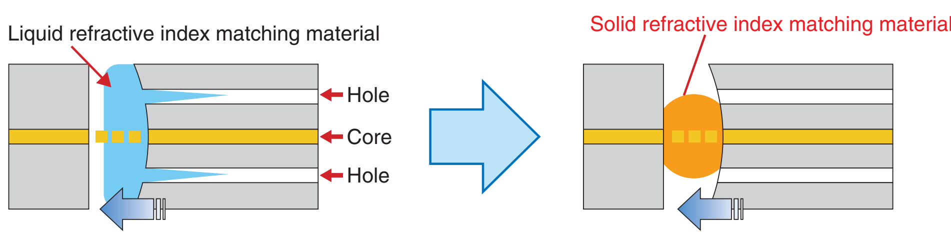



Fig. 4. HAF splice components with liquid and solid refractive index matching materials.

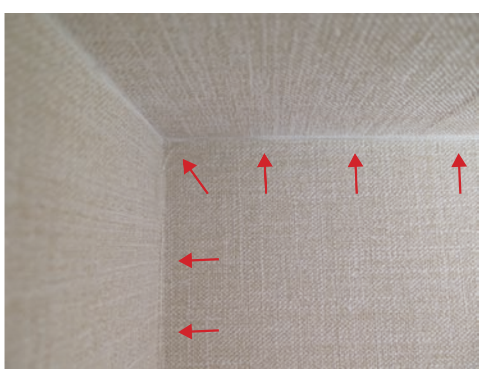


Fig. 5. Image of in-house wiring.

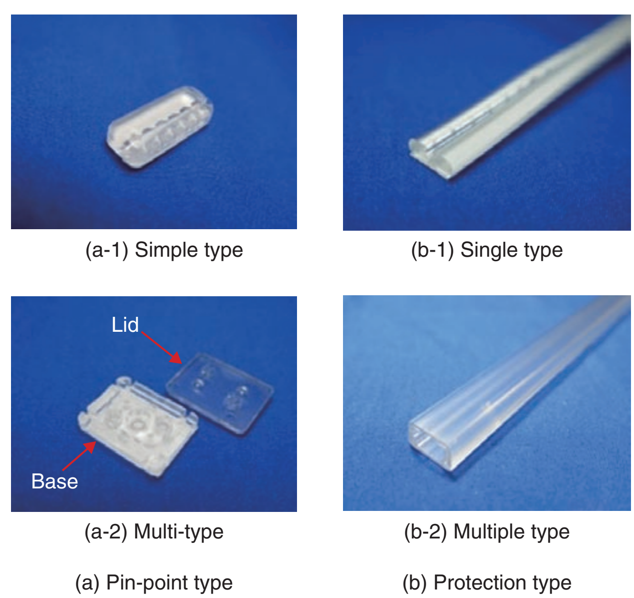



Fig. 6. Fixing components.

developed a single-type fixing component of the protection type to be used in areas where it is likely to be touched by customers. The protection-type of fixing component is also available in a multiple type, providing greater flexibility.

## 4. Conclusion

We introduced in this article our newly developed invisible optical fiber. We will continue to promote the introduction of optical fiber in cooperation with business companies and to support the business companies in deploying the fiber.

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# Utilization of APIs for B2B2X Business Model

*Mayumi Takahashi*

## Abstract

The NetroSphere concept proposed by NTT laboratories aims to divide network functions into small modular components and to flexibly assemble those components. This makes it possible to quickly form proportional networks that can offer required functionality according to user needs. As a result, carrier networks will achieve enhanced flexibility and elasticity while also drastically reducing costs. This article introduces the architecture to provide network functions and resources via APIs (application programming interfaces) to collaboration partners such as service developers.

*Keywords: API, collaboration, NetroSphere*

## 1. Introduction

The NetroSphere concept is a future network vision proposed by NTT laboratories [1]. The concept enables network functions to be divided into small modular components, which can then be flexibly assembled. This makes it possible to quickly form proportional networks that can offer required functionality in accordance with the user's needs for B2B2X (business-to-business-to-X) business models where various service partners and communication providers collaborate to provide services. This will increase the flexibility and elasticity of carrier networks while also drastically reducing costs.

Web-API[*1] (API) is considered to be one of the key technologies to achieve the NetroSphere concept. In this article, the architecture that provides network functions and resources via APIs and design rules for the APIs are explained.

## 2. Trends in usage of APIs for collaboration

### 2.1 Trends of service providers and overseas telecom operators

Well-known service providers such as Twitter, Facebook, and Amazon Web Service expose APIs in order to provide their own functions and information. Some large overseas telecom operators have also started providing network functions such as call control and payment services and have organized promotional programs such as ideathons and hackathons to bring business ideas into shape [2, 3].

Our view is that providing network functions via APIs will bring two advantages to these service providers and telecom operators:

1) Growth in revenue: When they provide functions and resources via APIs, collaboration partners can create new services with those functions and resources. Service providers and telecom operators can earn revenue by charging for the use of functions and resources that are provided via APIs.
2) Reduction in operating expenses (OPEX): Providing operational functions via APIs simplifies operational cooperation with collaboration companies. It permits business process automation and reduces OPEX.

### 2.2 Trends in standardization

Mobile telecom operators provide network functions via APIs to their collaboration partners. The

*1 Web API: An API (application programming interface) is an interface to exchange information between software components. Web API is one kind of API. Via an API, an application can call external functions provided by other software components or applications.

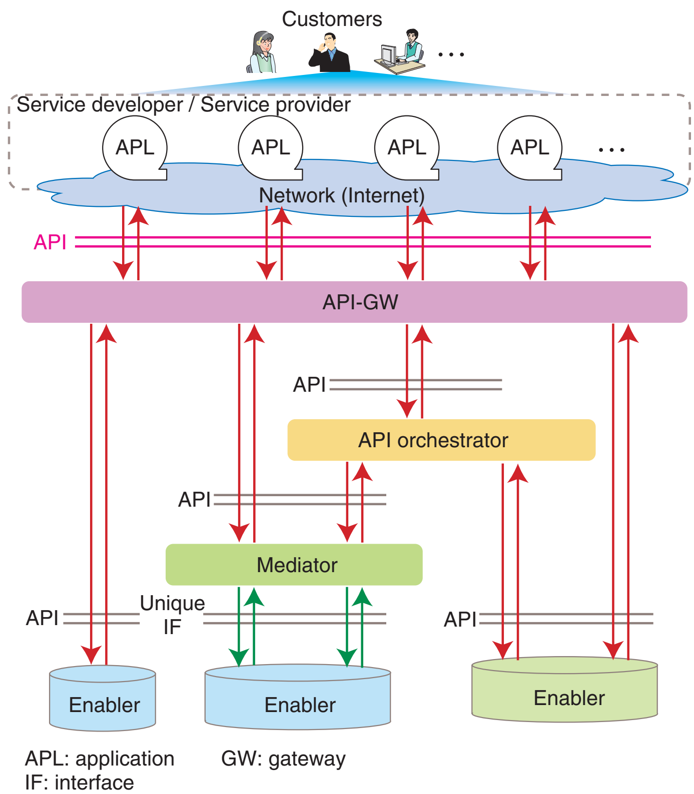


Fig. 1. API-providing architecture.

specifications of these APIs differ from operator to operator. This forces collaboration partners to write operator-specific programs. OneAPI is a set of APIs supported by the GSM Association (GSMA)*2 that defines API specifications for elements such as SMS (Short Messaging Service)/MMS (Multimedia Messaging Service), device capabilities, and payments [4]. AT&T provides some APIs according to these specifications.

The TeleManagement Forum (TM Forum)*3 has started to define API specifications for the interface between these business processes in order to facilitate the automation of business processes of telecom operators. TM Forum published some operational specifications such as those for trouble tickets and product ordering. Further, in the Open Digital Project, one of TM Forum's strategic programs, discussions have been initiated on the reference architecture called the Digital Service Reference Architecture (DSRA), which allows collaboration partners to create applications with a number of digital services provided via APIs [5].

As previously mentioned, some standardization organizations have defined the specifications of APIs, but their scope is limited. Thus, most operators provide APIs designed according to their own rules.

## 3. Technical considerations in providing network functions via APIs

We consider that APIs represent one of the key technologies to achieve the NetroSphere concept and that they will be effective in providing the architecture for NetroSphere.

### 3.1 API-providing architecture

The architecture being studied to provide network functions via APIs is shown in **Fig. 1**. This architecture consists of three functional units: the mediator

*2 GSMA: GSMA is an association of mobile operators and related companies devoted to supporting the standardization, deployment, and promotion of the GSM mobile telephone system.

*3 TM Forum: TM Forum is a non-profit industry association for service providers and their suppliers in the telecommunications and entertainment industries. TM Forum defines reference models of interfaces between business processes and data models.

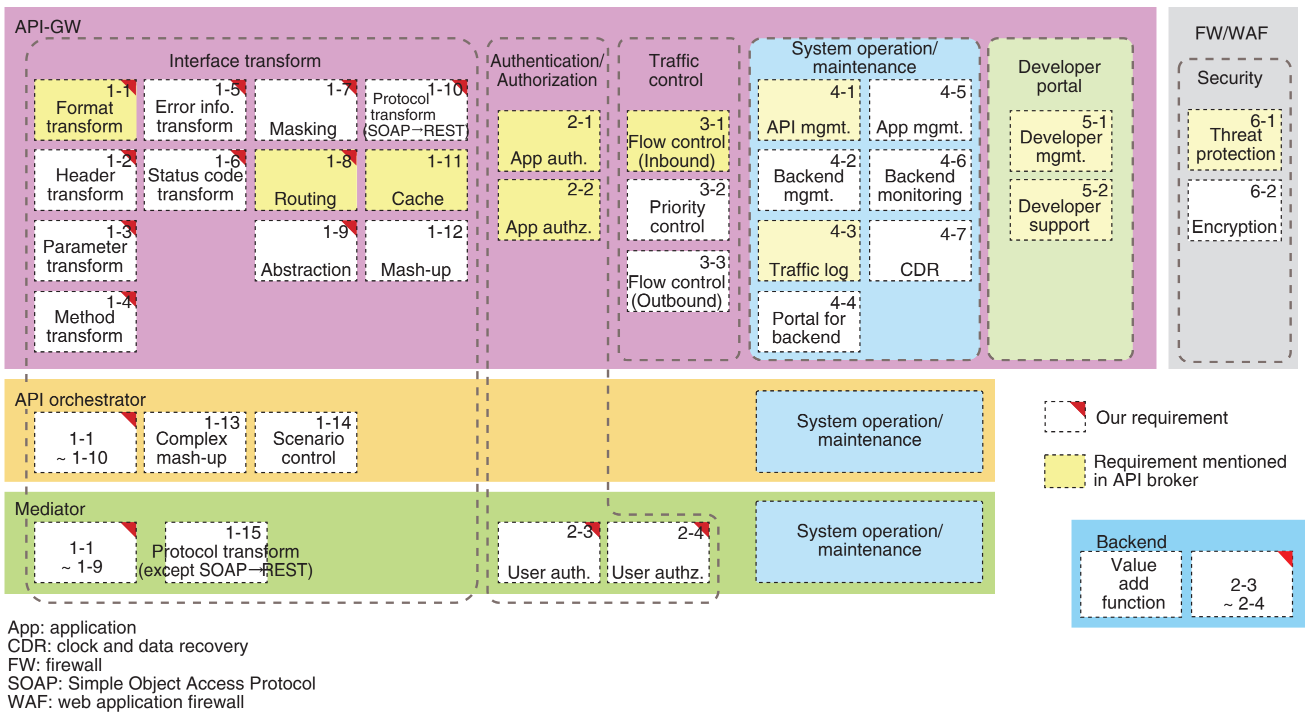


Fig. 2. Function deployment.

unit for protocol transformation, the API orchestrator unit for scenario control and API mash-up, and the API-GW (gateway) unit for authorization and traffic control. The details of these functions are described here and shown in **Fig. 2**.

(1) Mediator unit

Many existing operational systems have a unique interface to enable interconnection with other such systems. Our view is that it would be advantageous for network functions to be provided via representational state transfer (REST) APIs because the REST API style is familiar to service developers. Thus, we introduced the mediator unit to transform the unique interface into the REST API style.

(2) API orchestrator unit

Telecom operators do not want to directly expose their own backend systems such as their customer management and billing systems from the viewpoint of protecting the security of their systems and avoiding unnecessary complexity. The API orchestrator unit provides API abstraction and scenario control functions, which meet telecom operator requirements.

(3) API-GW unit

Service developers ordinarily have to call each end-point that differs from system to system when they use network functions provided by different systems. Moreover, each system may provide different API specifications such as those for the data format. This is not helpful to service providers. Thus, we introduced the API-GW unit to centralize end-points and absorb differences in API specifications. In addition, the API-GW provides a common function to expose APIs such as those for traffic control and authorization. The API-GW unit is divided into three functional units that have specific functions.

1) API broker: API broker provides a security protection function, authentication and authorization function (API-key, OAuth), and a traffic control function in accordance with the terms of agreement and system state, and an interface transformation function in accordance with design rules described in section 3.2.
2) Developer portal: The developer portal provides service developers with a management function and documents such as manuals and sample code.
3) System operation/maintenance: The system operation/maintenance function unit provides operational functions for the API-GW operator to manage enablers, APIs, and applications developed by service developers and also to

manage the state of the API-GW.

### 3.2 API design rules

The design rules of REST APIs such as the API naming rule and data format description rule are flexible. Thus, specifications of APIs provided by telecom operators may differ from operator to operator. In addition, APIs may differ from vendor to vendor even if the functions are the same because these APIs are designed according to vendor-specific design rules. This may cause difficulties when telecom operators renew their equipment.

To simplify things for service developers, we believe that telecom operators should provide APIs designed according to a unified design rule based on one of the two rules below.

1) Function-independent rules: These rules define common rules that apply regardless of the type of functions; they include naming rules of URLs, rules for determining data format, and authentication methods of APIs.
2) Function-dependent rules: These rules define functions themselves such as those for call control, service orders, and trouble tickets.

Our first step will be to focus on function-independent rules.

## 4. Future prospects

This article reviewed the API-related trends followed by overseas telecom operators. An architecture that provides network functions via APIs was also discussed along with API design rules. Our aim is to standardize the proposed architecture and describe the API design rules at a TM Forum event. We will define the aforementioned architecture that allows service developers to create applications with multiple functions provided by telecom operators.

In parallel, we will start providing an API testbed called Atelier N [6], which is positioned as a collaborative program. We would like to use this program to discuss issues related to creating services and providing functions with our collaboration partners such as service developers and function providers. We also plan to evaluate the proposed architecture and design rules with our collaboration partners.

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[3] Website of Orange Partner, https://www.orangepartner.com/
[4] GSMA, API Exchange, http://www.gsma.com/oneapi/
[5] Website of TM Forum, https://www.tmforum.org/
[6] Website of Atelier N, https://developer.api-trial.jp/en/index.html

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She received a B.Ed. and M.E. in mechanical engineering from Saitama University in 1991 and 1993. She joined NTT in 1993 and began researching electro-magnetic compatibility for chassis of switching equipment and cables. She is currently conducting research on an API-providing architecture for the B2B2X business model.

# Latest TM Forum Developments

*Shingo Horiuchi*

**Abstract**

As an established thought leader in telecom operations related standards, the TeleManagement (TM) Forum is making good progress on three strategic programs in addition to its ongoing work in developing operation systems. This article provides an overview of recent TM Forum initiatives concerning service interaction between telecom operations and over-the-top content toward virtualization, the proof of concept Catalyst project, and overall TM Forum related developments.

*Keywords: TM Forum, Frameworx, Catalyst project*

## 1. Introduction

The TeleManagement (TM) Forum [1] was originally established in 1988 as the OSI (Open Source Initiative)/Network Management Forum and today has more than 950 corporate members and well over 90,000 technicians and engineers working to fine-tune telecom operations-related industry standards to promote improved interoperability. TM Forum focuses primarily on standards related to the development of operation systems (business processes, information models, applications). It produces Frameworx, an updated suite of best practices and business metrics that define key performance indicators and key quality indicators for frameworks and operations for automatically generating interfaces. Frameworx is released biannually; the current version is Frameworx 15.0. As of this writing, the upgrade to Frameworx 15.5 was scheduled for December 2015.

Investigative work in preparation for a new release of Frameworx begins with face-to-face meetings of working-level drafters during TM Forum Action Week, which is held twice a year. These meetings are followed up with regular teleconferences and collaborative liaisons to complete the drafting work.

Frameworx specifications are deliberated on by the members and then organized as a deliverable document divided into units called *projects*. Issues have traditionally taken the form of projects as the basic units making up the Frameworx standard. Over the last few years, project discussions related to strategic programs have become prominent (as discussed in greater detail below), and the content of the various projects is discussed in parallel and reflected in the main body of Frameworx.

## 2. Telecom operations standardization

Standardization of telecom operations involves careful consideration of how equipment under management is linked with the business processes of the operators. The equipment to be managed goes beyond conventional equipment and systems that comply with ITU-T* recommendations. The equipment dealt with in recent years involves virtual technology, specifically, equipment for network function virtualization (NFV) specified by the European Telecommunications Standards Institute (ETSI) and network function virtualization/software-defined networking (NFV/SDN) dealt with by the Open Network Foundation (ONF). The standardization process involves building liaison relationships with ETSI, ONF, and other organizations. We should also note that whereas ETSI and ONF are primarily focused on management at the network control level, TM Forum also studies operations as a business process and is not just focused on control alone.

* ITU-T: International Telecommunication Union, Telecommunication Standardization Sector

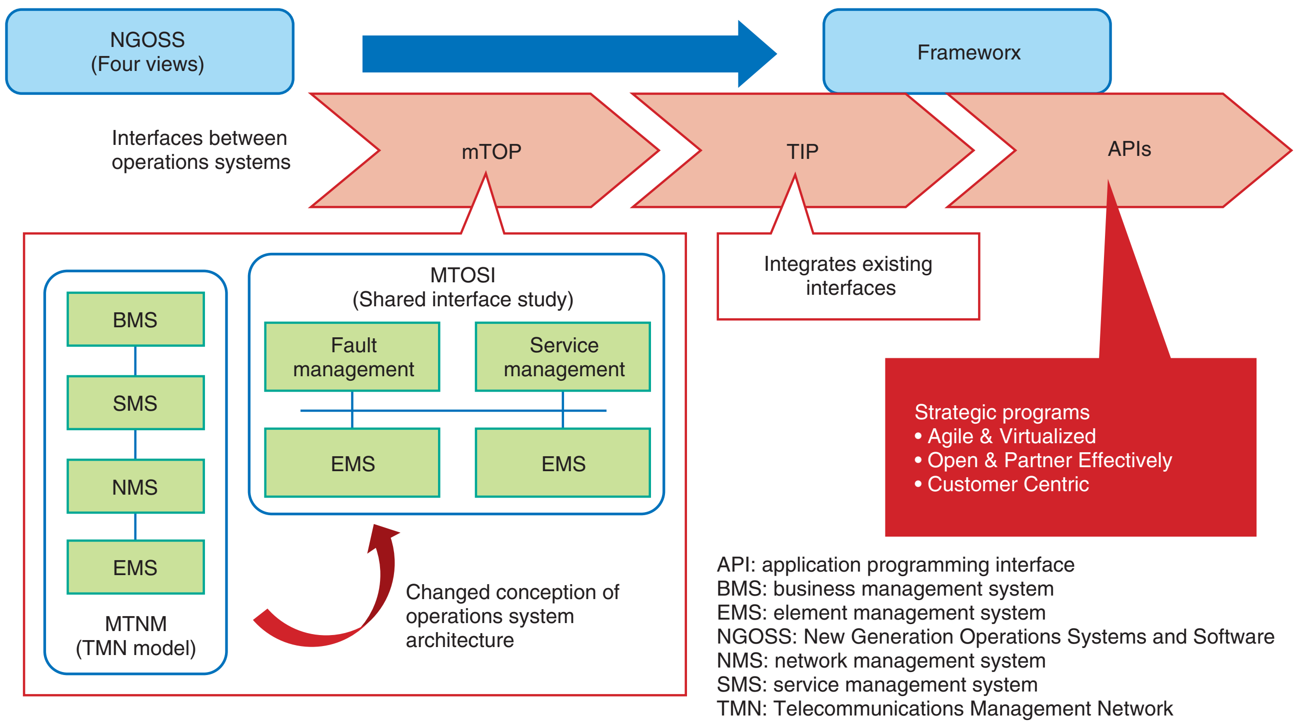



Fig. 1. Transformation in concept of interfaces.

## 3. Frameworx and three strategic programs

### 3.1 Work on Frameworx

TM Forum has been working on the Frameworx suite for some time and has recently placed particular emphasis on the following elements.

(1) Business Process Framework (eTOM)

The enhanced Telecom Operation Map (eTOM) is a business process organized based on phases and Shared Information/Data Model (SID) domains.

(2) Information Framework (SID)

SID is organized not as a concrete data model of how information is managed and distributed but rather as an information model.

(3) Application Framework (TAM)

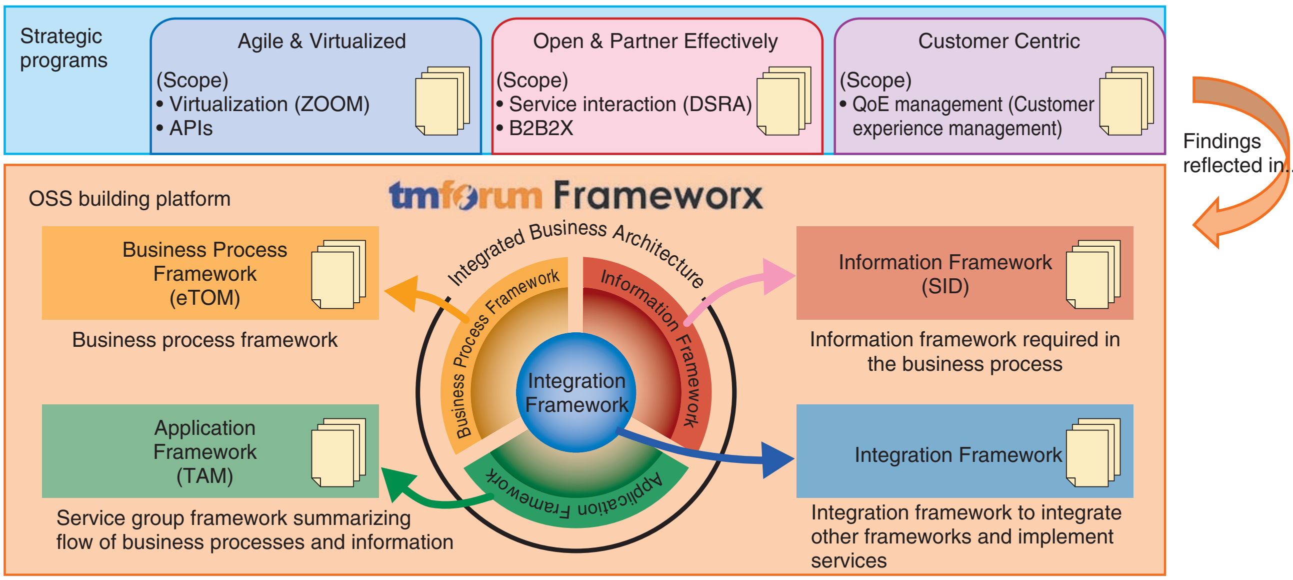
TAM (Telecom Application Map) is a standard framework for organizing and mapping operation support system (OSS) capabilities using relationships with eTOM and SID.

Business processes involve more than operational processes such as fulfillment, assurance, and billing. They also focus attention on strategy (decision-making), readiness (migration, procurement), and other factors.

In terms of interface trends, we have already evaluated MTNM (Multi Technology Network Management) and MTOSI (Multi-Technology Operations System Interface) as part of mTOP (multi Technology Operations Program), and we are making headway in integrating interfaces with other conventional interfaces through TIP (TM Forum Integration Program). This reflects the changes in operations system architectures and the transformation in the concept of interfaces (**Fig. 1**). More specifically, we are now pushing beyond modeling of network equipment capabilities for each protocol by ITU-T and other traditional organizations by integrating wireless and wireline network equipment models. As conventional information models expand, there is growing momentum to develop models that incorporate virtual networks as well.

### 3.2 Strategic programs

The policy to expand the Frameworx suite was launched two years ago with the decision to pursue three strategic programs. Efforts were focused on dealing with the introduction of virtualization and business-to-business-to-X (B2B2X) service. More specifically, efforts were focused on the following




DSRA: Digital Service Reference Architecture
QoE: quality of experience
ZOOM: Zero-touch Orchestration, Operations and Management

Fig. 2. Three strategic programs.

three strategic programs (**Fig. 2**), which are introduced here and described in more detail in the following sections.

(1) Agile & Virtualized program

This program is centered on virtual operations and security.

(2) Open & Partner Effectively program

This program is focused on scenarios through service interaction, for example, architecture and Internet of Things (IoT) to achieve an open digital ecosystem.

(3) Customer Centric program

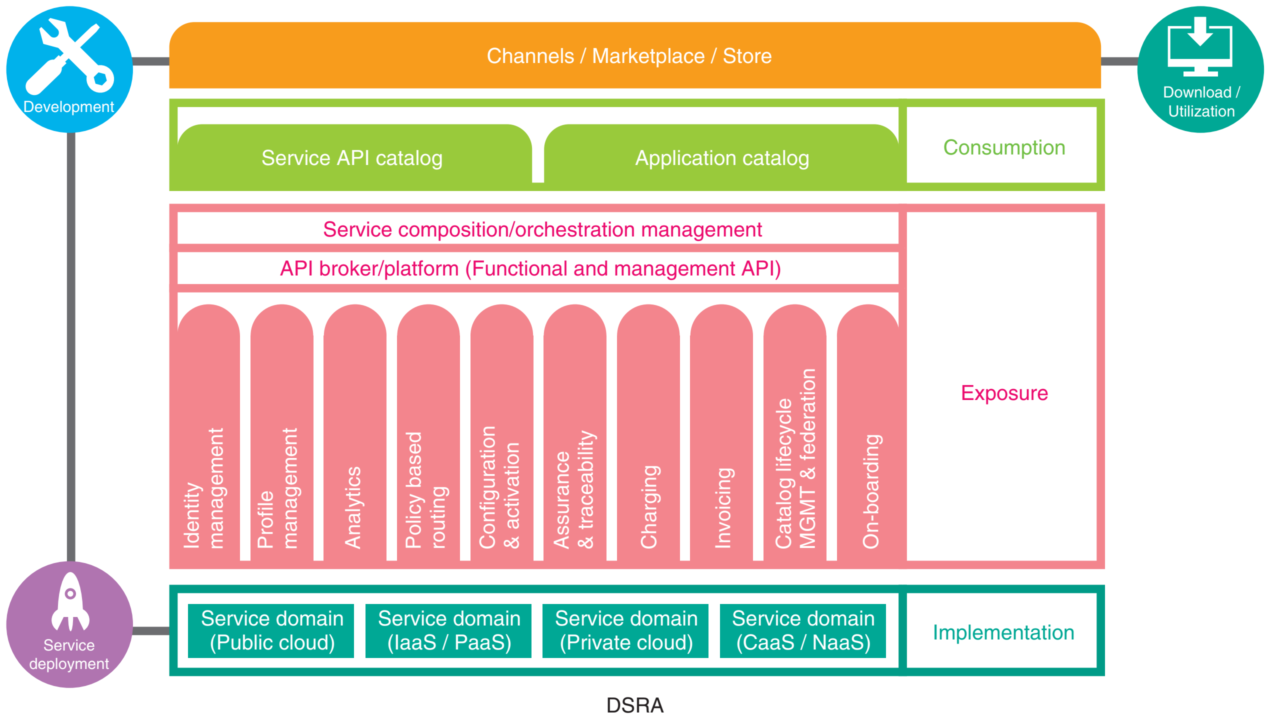
The emphasis of this program is big-data analysis to evaluate customer experience management and applicable metrics based on criteria for assessing customer experience.

## 4. Open & Partner Effectively program and DSRA

The Open and Partner Effectively program focuses on service interaction among telecom operators and schemes for quickly creating new value. More specifically, the program explores scenarios based on B2B2X business best practices, a service interaction architecture (i.e., Digital Service Reference Architecture (DSRA)) (**Fig. 3**), and concrete representational state transfer-based application programming interfaces (APIs) for promoting service interaction. The DSRA is essentially a scheme in which digital services—private cloud, public cloud, NaaS (network as a service)—provided by the service domain can offer interactive services using an API broker based on a service API catalog.

## 5. Agile & Virtualized program and ZOOM

The Agile & Virtualized program is committed to the Zero-touch Orchestration, Operations and Management (ZOOM) project for exploiting NFV and SDN in the operation of virtual networks. Primary objectives of the ZOOM project are to curtail capital and operating expenditures through virtualization, while creating service opportunities through rapid deployment of new services. Not only has this promoted discussion of the OSS architecture and an information model under management, it has also led to the definition of a framework supporting procurement of VNF (Virtual Network Function). One challenge faced by the OSS architecture is that the sharp demarcation between the network control layer and the operation support layer that has existed until now becomes rather blurry when dealing with virtual technology.




CaaS: cloud as a service
IaaS: infrastructure as a service
MGMT: management
PaaS: platform as a service

Fig. 3. Architecture for service interaction.

## 6. Customer Centric program

The Customer Centric program deals with a framework for improving customer satisfaction that can be adopted as a quality metric to assess customer enjoyment and experience using telecom services. This involves defining the lifecycle of customers, deriving a customer access channel metric for each phase of the lifecycles, then developing a big data analysis based reference architecture for calculating the metric.

## 7. Catalyst project

The goal of TM Forum's Catalyst project is to verify the documented effectiveness of the Frameworx suite as a standard and then continue to enhance and refine the standard document. In the Catalyst project, dynamics using Frameworx standards prepared by more than four software vendors are currently being validated that will be applied to scenarios assembled by more than two telecom operators. With this initiative, new events including TM Forum Live! and Catalyst InFocus have largely superseded the biennial TM Forum Management World that was held in earlier years, and they provide representatives of corporate TM Forum members an opportunity to provide feedback and offer comments that will be incorporated into future releases of the Frameworx standard.

No less than 20 Catalysts were showcased at TM Forum Live! 2015, which was held in Nice, France in the first week of June. Note that half of these Catalysts involved virtualization, which clearly indicates the enormous interest among members in the operational aspects of virtualization.

## 8. Overall trends

Since it was first established, TM Forum has primarily been concerned with the development of telecom-oriented operations. Just a few years ago, most discussions on the operation layer were centered on network management, but today we find that upper layer customer management and the business management layer are also widely discussed. Indeed, we find that even in lectures by TM Forum executives, the speakers tend to mention areas where sharing is achieved by standardizing telecom operator network management and service management, and areas where differentiation is highlighted as a legitimate business strategy. Discussion of business metrics and other topics in Frameworx clearly reflects these trends.

We have also recently begun to see more discussion on operations geared toward IoT and 5G (fifth-generation mobile networks), which should open the way to establishing cooperation with many OTT operators. We are thus making good headway in building liaison relationships with other related standards organizations. One initiative that clearly illustrates these proactive collaborative efforts is the joint meetings with other standards-making bodies at TM Forum Action Week, TM Forum Live!, and other conferences organized by TM Forum.

## 9. Future prospects

The NTT Group plans to move forward with wholesale services based on virtual and B2B2X model-based interactive services featuring open, competitive architectures and interfaces. Upstream activities are currently underway in the investigative projects of TM Forum's three strategic programs, with the idea that these new insights will be reflected in future Frameworx document releases.

The Forum also continues to be actively involved in the proof of concept Catalyst project to verify the viability of operational scenarios by combining commercialized technologies. The findings obtained in the Catalyst project were presented at Catalyst InFocus 2015 [2] held in Dallas, Texas in early November 2015.

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He received a B.E. and M.E. in engineering from the University of Tokyo in 1999 and 2001. He joined NTT Access Network Service Systems Laboratories in 2001. He has been researching and developing access network operation systems. He has been involved in the standardization work for operation support systems in TM Forum as a member of the ZOOM project since 2014. He is a member of the Institute of Electronics, Information and Communication Engineers.

# External Awards

### Photonics in Switching 2015 Best Paper Award

**Winner:** Salah Ibrahim, Tatsushi Nakahara, Hiroshi Ishikawa, and Ryo Takahashi, NTT Device Technology Laboratories
**Date:** September 24, 2015
**Organization:** Photonics in Switching 2015 Committee

For "An Ultralow-power Optical Label Processor for 100-Gbps Optical Packet Switching."

A novel label processor subsystem for 100-Gbps (25-Gbps × 4 Lambdas) burst-mode optical packets has been developed with a significant reduction of power consumption and latency, based on an enhanced optoelectronic serial-to-parallel converter and a novel optical-trigger-pulse generator that consists of a semiconductor optical amplifier and a single-chip optoelectronic integrated circuit high-speed current driver.
**Published as:** S. Ibrahim, T. Nakahara, H. Ishikawa, and R. Takahashi, "An Ultralow-power Optical Label Processor for 100-Gbps Optical Packet Switching," Proc. of Photonics in Switching 2015, ThII2-4, Florence, Italy, Sept. 2015.

### APCC2015 Best Paper Award

**Winner:** Kazuhisa Yamada, NTT Network Innovation Laboratories; Akihiro Nakao, the University of Tokyo; Yasushi Kanada, Hitachi, Ltd.; Yoshinori Saida, NEC Corporation; and Koichiro Amamiya, Fujitsu Laboratories Ltd.
**Date:** October 15, 2015
**Organization:** APCC2015 (21st Asia-Pacific Conference on Communications) Award Committee

For "VNode Infrastructure Enhancement - Deeply Programmable Network Virtualization."
**Published as:** K. Yamada, A. Nakao, Y. Kanada, Y. Saida, and K. Amamiya, "VNode Infrastructure Enhancement - Deeply Programmable Network Virtualization," Proc. of APCC2015, Kyoto, Japan, Oct. 2015.

### WCSP 2015 Best Paper Award

**Winner:** Keisuke Sato, Yuichi Kawamoto, Hiroki Nishiyama, Nei Kato, Graduate School of Information Sciences, Tohoku University; and Yoshitaka Shimizu, NTT Network Innovation Laboratories
**Date:** October 16, 2015
**Organization:** WCSP 2015 (7th International Conference on Wireless Communications and Signal Processing)

For "A Modeling Technique Utilizing Feedback Control Theory for Performance Evaluation of IoT System in Real-time."

In this paper, we focus on the modeling aspect for evaluating the performance of a real-time Internet of Things (IoT) system. Specifically, our proposed model is constructed by utilizing feedback control theory.
**Published as:** K. Sato, Y. Kawamoto, H. Nishiyama, N. Kato, and Y. Shimizu, "A Modeling Technique Utilizing Feedback Control Theory for Performance Evaluation of IoT System in Real-time," Proc. of WCSP 2015, Nanjing, China, Oct. 2015.

### IEEE Photonics Society Japan Chapter Young Scientist Award

**Winner:** Satomi Katayose, NTT Device Technology Laboratories
**Date:** October 28, 2015
**Organization:** IEEE Photonics Society Japan Chapter

For "1×8 Silicon-silica Hybrid Thermo-optic Switch with Multi-chip Configuration Based on Optical Phased Array."
**Published as:** S. Katayose, Y. Hashizume, and M. Itoh, "1×8 Silicon-silica Hybrid Thermo-optic Switch with Multi-chip Configuration Based on Optical Phased Array," Proc. of MOC'15 (the 20th Microoptics Conference), Fukuoka, Japan, Oct. 2015.

### ISPACS 2015 Best Paper Award

**Winner:** Takayuki Nakachi and Tatsuya Fujii, NTT Network Innovation Laboratories
**Date:** November 11, 2015
**Organization:** ISPACS 2015 (The 2015 International Symposium on Intelligent Signal Processing and Communication Systems) Technical Program Committee

For "Layered Lossless Video Coding Based on Slepian-Wolf Theorem."
**Published as:** T. Nakachi and T. Fujii, "Layered Lossless Video Coding Based on Slepian-Wolf Theorem," Proc. of ISPACS 2015, pp. 652–657, Bali, Indonesia, Nov. 2015.

# Papers Published in Technical Journals and Conference Proceedings

### Verifying Power Distribution Network with ZDDs

T. Inoue, N. Yasuda, S. Kawano, Y. Takenobu, S. Minato, and Y. Hayashi

Proc. of ISMP 2015 (the 22nd International Symposium on Mathematical Programming), Pittsburg, USA, July 2015.

Power distribution networks should be restored by reconfiguring switches automatically, given that several feeders are interrupted in a severe accident. The network's design has to guarantee that it is restorable under any possible failure, but it is a computationally hard task to examine all possible failures. This paper proposes a novel ZDD (zero-suppressed binary decision diagram) method to find all the critical (unrestorable) line cuts with great efficiency to verify the network design. The method includes a fast screening algorithm based on hitting set enumeration, which is often used in data-mining. Thorough experiments reveal that the proposed method can find thousands of unrestorable cuts from the trillions of possible cuts in a large 432-Bus network.

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### Stable Load Balancing with Overlapping ID-space Management in Range-based Structured Overlay Networks

K. Mizutani, T. Inoue, T. Mano, O. Akashi, S. Matsuura, and K. Fujikawa

Computer Software, Vol. 32, No. 3, pp. 101–110, August 2015.

This paper proposes a novel scheme that distributes, fairly, the loads without node migration and with little data reallocation, by sharing some identification (ID)-space regions between neighboring nodes. Our overlapping ID-space management scheme derives the optimal overlap based on kernel density estimations; the query loads based on the statistical theory are used to calculate the best overlap regions. This calculation is executed in a distributed manner with no central coordinator. We conduct thorough computer simulations, and show that our scheme alleviates the worst node load by 20–90% against existing techniques without node migration and with the least data reallocation.

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### Viewpoint Image Generation for Head Tracking 3D Display Using Multi-camera and Approximate Depth Information

M. Date, H. Takada, and A. Kojima

Journal of SID, Vol. 23, No. 8, pp. 340–346, August 2015.

A simple and high image quality method for viewpoint image synthesis from multi-camera images for a stereoscopic 3D display using head tracking is proposed. In this method, slices of images for depth layers are made using approximate depth information, the slices are linearly blended corresponding to the distance between the viewpoint and cameras at each layer, and the layers are overlaid from the perspective of viewpoint. Because the linear blending automatically compensates for depth error because of the visual effects of depth-fused 3D (DFD), the resulting image is natural to the observer's perception. Smooth motion parallax of wide depth range objects induced by viewpoint movement for left-and-right and front-and-back directions is achieved using multi-camera images and approximate depth information. Because the calculation algorithm is very simple, it is suitable for real time 3D display applications.

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### Novel Applications of and Experiments on Programmable Infrastructures

Y. Minami and K. Yamada

Proc. of MASONS (IEEE International Workshop on Manageability and Security of Network Function Virtualization and Software Defined Network) 2015, Las Vegas, USA, August 2015.

We show novel applications as use cases and experiment results on programmable infrastructures. We realized multicast streaming and adaptive bit rate streaming by automatically deploying video processing functions in a slice. Experimental results showed that we can enhance service functionalities and use resources efficiently with programmable infrastructures.

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### Low Power Driving Techniques for 1-pixel Displays

H. Manabe, M. Date, H. Takada, and H. Inamura

Proc. of IAS 2015 (the 50th IEEE Industry Applications Society Annual Meeting), 2015-ILDC-0339, Dallas, USA, October 2015.

Two techniques to reduce the power needed for driving 1-pixel LCDs (liquid crystal displays) are proposed. The first one is the use of multiple capacitors, and the second is dividing the LCD into two to lower the drive voltage. Simulations show that large capacitance and many capacitors can reduce the power, and stacking two thin LCDs driven by lower voltage maximizes the effect of the proposed technique, especially for small LCDs. An experiment on the former technique using actual PDLCDs (polymer dispersed liquid crystal displays) confirms that it works as effectively as the simulation implies. The overall energy consumption of large PDLCDs is reduced more than 70%.

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### Development of a Handset for NGN Wideband Telephone Service Trial

M. Okamoto, K. Noguchi, Y. Hiwazaki, and Y. Haneda

The Journal of the Acoustical Society of Japan, Vol. 71, No. 11, pp. 581–589, November 2015 (in Japanese).

Since 2008, a high-quality IP telephone service has been provided over a Next Generation Network (NGN) developed by Nippon Telegraph and Telephone Corporation (NTT) Group of Japan. Prior to the commencement of service provision, a wideband telephone handset was developed on an experimental basis and tested in a field trial to verify service validity. The handset demonstrated improved characteristics over those of conventional telephone handsets.

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### Low-power Driving Technique for 1-pixel Display Using an External Capacitor

H. Manabe, M. Date, H. Takada, and H. Inamura

IEICE Transactions on Electonics, Vol. E98-C, No. 11, pp. 1015–1022, November 2015.

Liquid crystal displays (LCDs) are suitable as elements underlying wearable and ubiquitous computing thanks to their low power consumption. A technique that uses less power to drive 1-pixel LCDs is proposed. It harvests the charges on the LCD and stores them in an external capacitor for reuse when the polarity changes. A simulation shows that the charge reduction depends on the ratio of the capacitance of the external capacitor to that of the LCD and can reach 50%. An experiment on a prototype demonstrated an almost 30% reduction with large 1-pixel LCDs. With a small 10 x 10 $mm^2$ LCD, the overhead of the micro-controller matched the reduction, so no improvement could be measured. Though the technique requires longer time for polarity reversal, we confirm that it does not significantly degrade visual quality.

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**Network Clock System that Ensures a High Level of Frequency Accuracy**

S. Fujikawa

IEICE Transactions on Communications, Vol. E98-B, No. 11, pp. 2212–2226, November 2015.

This paper proposes a network clock system that detects degradation in the frequency accuracy of network clocks distributed across a network and finds the sources of the degradation. This system uses two factors to identify degradation in frequency accuracy and an algorithm that finds degradation sources by integrating and analyzing the evaluation results gathered from the entire network.

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**Differential Reliability Path Accommodation Design and Reconfiguration in Virtualized Multi-layer Transport Network**

A. Kadohata, T. Tanaka, A. Watanabe, A. Hirano, H. Hasegawa, and K. Sato

IEICE Transactions on Communications, Vol. E98-B, No. 11, pp. 2151–2159, November 2015.

In this paper, we propose differentiated reconfiguration to address the trade-off relationship between accommodation efficiency and disruption risk in virtualized multi-layer transport networks. The reconfiguration considers service classes defined as a combination of including or excluding a secondary path and allowing or not allowing reconfiguration. To implement the proposed network, we propose a multi-layer redundant path accommodation design and reconfiguration algorithm. A reliability evaluation algorithm is also introduced. Numerical evaluations show that when all classes are divided equally, the equipment cost can be reduced by approximately 6%. The proposed reconfigurable networks are shown to be a cost-effective solution that maintains reliability.

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**Real-time Robust Formant Estimation System Using a Phase Equalization-based Autoregressive Exogenous Model**

H. Oohashi, S. Hiroya, and T. Mochida

Acoustical Science and Technology, Vol. 36, No. 6, pp. 478–488, November 2015.

This paper presents a real-time robust formant tracking system for speech using a real-time phase equalization-based autoregressive exogenous model (PEAR) with electroglottography (EGG). Although linear predictive coding (LPC) analysis is a popular method for estimating formant frequencies, it is known that the estimation accuracy for speech with high fundamental frequency $F_0$ would be degraded since the harmonic structure of the glottal source spectrum deviates more from the Gaussian noise assumption in LPC as its $F_0$ increases. In contrast, PEAR, which employs phase equalization and LPC with an impulse train as the glottal source signals, estimates formant frequencies robustly even for speech with high $F_0$. However, PEAR requires higher computational complexity than LPC. In this study, to reduce this computational complexity, a novel formulation of PEAR was derived, which enabled us to implement PEAR for a real-time robust formant tracking system. In addition, since PEAR requires timings of glottal closures, a stable detection method using EGG was devised. We developed the real-time system on a digital signal processor and showed that for both the synthesized and natural vowels, the proposed method can estimate formant frequencies more robustly than LPC against a wider range of $F_0$.

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**Mode-selective Coherent Detection Technique for Low-complexity Mode Division Multiplexing Systems**

F. Hamaoka, S. Okamoto, K. Horikoshi, K. Yonenaga, A. Hirano, and Y. Miyamoto

Electronics Letters, Vol. 51, No. 23, pp. 1899–1900, November 2015.

The mode division multiplexing (MDM) signal transmitted in an optical multimode fibre link is usually received with multiple coherent receivers (RXs), resulting in an increase in RX system scale. A mode-selective coherent detection technique is proposed based on MDM-to-frequency division multiplexing (FDM) signal conversion scheme using an MDM and FDM local oscillator. The proposed technique uses only a single coherent RX to detect the MDM signal to achieve low-complexity MDM systems. The proposed mode-selective coherent detection technique is also experimentally shown. The experimental results show that a single coherent RX successfully receives the MDM signal.

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**Impacts of Burst Disturbance on Throughput and Connection Quality of ADSL System**

K. Ono, K. Okamoto, H. Tatemichi, and K. Takaya

Proc. of KJJC-2015 (2015 Korea-Japan EMT/EMC/BE Joint Conference), pp. 227–230, November 2015.

The relationship between duration of burst disturbances and the throughput/connection quality of digital communication was investigated in order to evaluate the impact of burst disturbances. In this paper, the impacts of the duration of burst disturbances with fixed frequency on Receive Bit Rate (RBR) and applied levels of burst disturbances causing Asymmetric Digital Subscriber Line (ADSL) reconnection were evaluated experimentally. As a result, it has been clarified that the RBR of an ADSL changes in accordance with the increased number of disturbed ADSL frames in response to the increased duration of burst disturbance, and ADSL reconnection tends to occur even if the applied level of burst disturbance is small because of the increased number of disturbed ADSL frames in response to the increased duration of burst disturbance.

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**Optically Observed Imbibition and Drainage of Wetting Fluid in Nanoporous Vycor Glass**

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The light scattering and absorption of nanoporous Vycor glass during imbibition and drainage of water exhibit the hysteresis of the white turbidity in the visible region and that of the absorbance peak in the near-infrared region. We analyzed the effect of changing humidity on each of the hystereses. The effect of changing humidity up to various values of maximum attained humidity on both hystereses showed that the amount of water in pores determines unsaturated optical hystereses in both regions.