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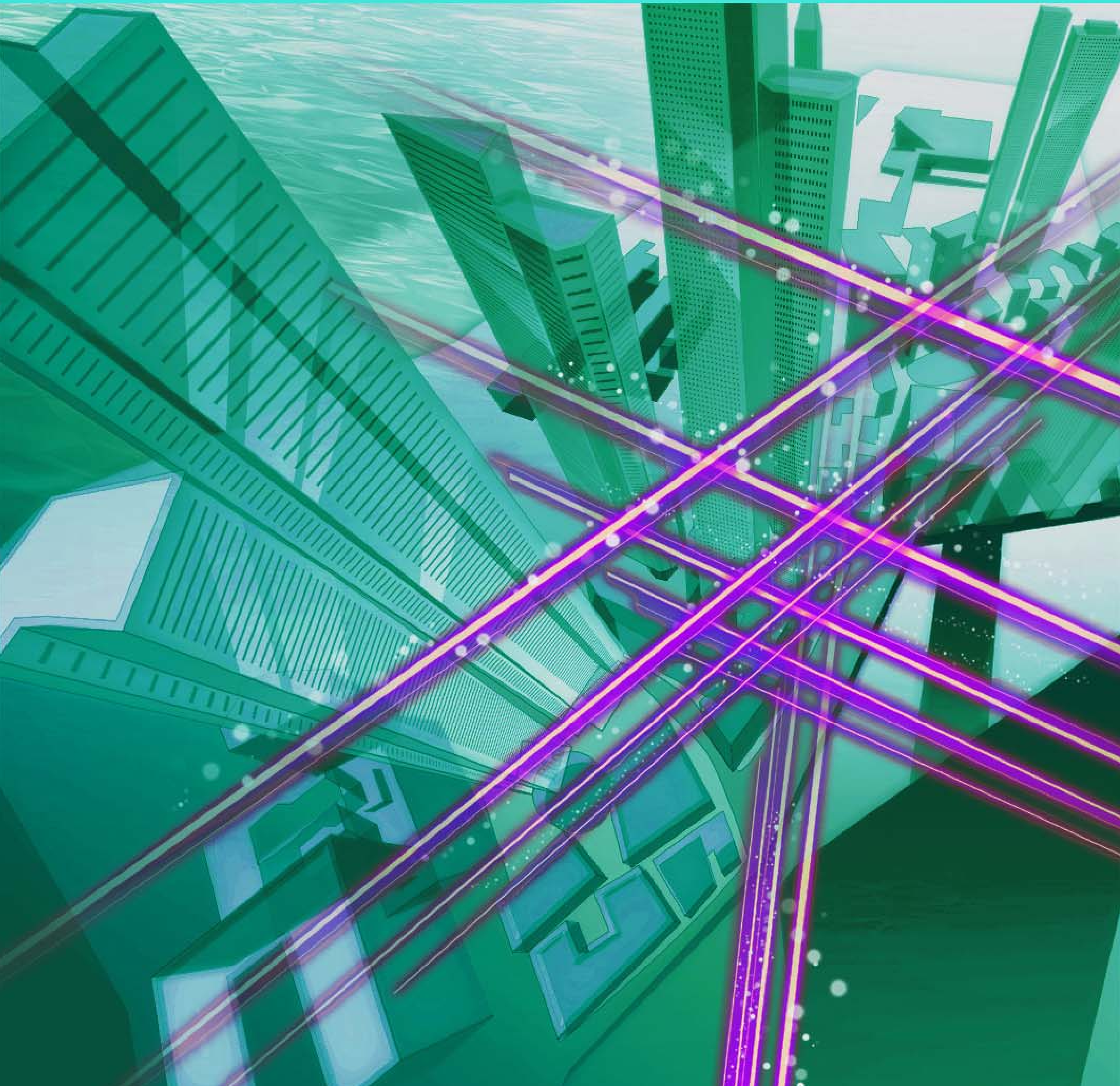

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Research Is Never Complete—It Will Finish When You Are Satisfied

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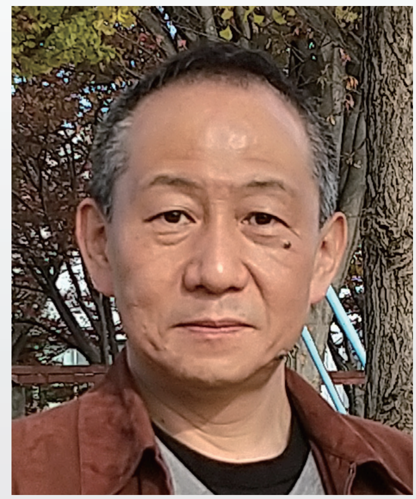

Abstract

To address the ever-increasing data-transmission capacity, it is necessary to develop technology that can increase such capacity 100 to 1000 times or more in the future. To meet this need, research on multi-core optical fibers is being conducted worldwide. Senior Distinguished Researcher Kazuhide Nakajima has developed multi-core optical fibers with transmission capacity more than 100 times greater than that of current optical fibers and the world's highest spatial-utilization efficiency and won top honors at a prestigious international conference. We interviewed him about the progress of his research and the attitude of a researcher aiming to achieve world firsts.

Keywords: multi-core optical fiber, space-division multiplexing, international standardization

Research and development of optical-fiber technologies that support continued development of optical-communication infrastructure

—Could you give us an overview of the research you are conducting and the activities you are involved in?

I'm involved in the research and development (R&D) of optical-fiber technologies that support continued development of optical-communication infrastructure that connects all types of people, things, and events. As traffic in core and submarine networks is expected to further increase, the current single-mode optical fibers will reach the limit of their transmission capacity, so technologies for higher transmission capacity will be required. Higher transmission capacity can be achieved by combining two technologies: for multiplexing and transmitting multiple laser beams and for increasing the number of cores (which are optical paths) in a single optical fiber. Working closely with related groups inside and outside NTT laboratories, we are researching and developing optical fibers having multiple cores in one optical fiber (i.e., *multi-core optical fiber*) for space-division-multiplexing (SDM) transmission. We are working on increasing the number of spatial channels and spatial-multiplexing density while fusing SDM optical-amplification technology and optical-control technology for transmission media. As we aim to implement these technologies, we are also researching and developing an innovative cabling technique that maximizes the characteristics of SDM optical fibers (**Fig. 1**).

Although we have developed optical fibers for

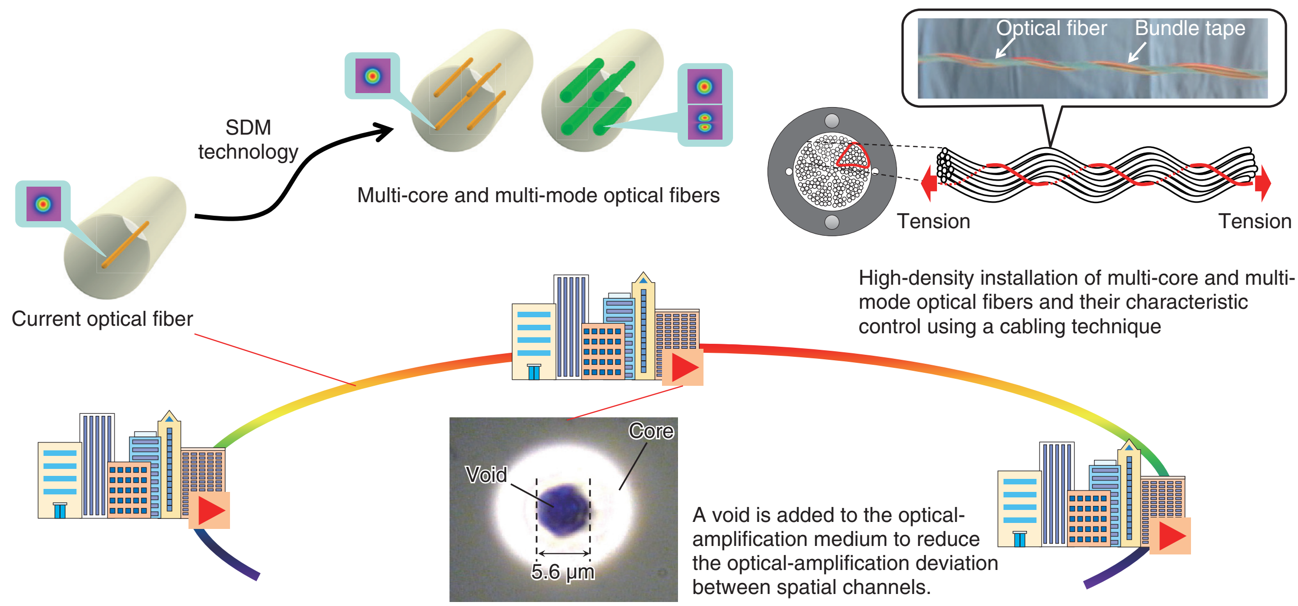

Fig. 1. Research on optical fibers for achieving SDM transmission.

increasing the speed and capacity of networks, such fibers can be used in other areas besides communications. The refractive index in an optical fiber slightly changes with a bending. External sound and vibration also cause a tiny change in the refractive index, and that results in the amplitude and phase variation in the scattered light in the optical fiber. Exploiting these characteristics would make it possible to use optical-fiber cables as sensors installed throughout society. Optical-fiber environmental-monitoring technology, which uses optical fibers as sensors, is expected to help address social issues such as managing facilities and predicting the deterioration of infrastructure (such as electric power, gas, water, and railways), understanding disaster situations, forecasting disasters on the basis of river and ground information, and providing city information such as traffic volume and traffic-jam forecast and weather forecasts. We are working on this new-value creation from the perspective of optical-fiber technology as one of our themes.

I am also involved in activities related to the international standardization of optical-fiber technology as my life's work. Once optical-communication infrastructure is installed, it cannot be easily changed or upgraded. For R&D of optical-communication infrastructure, therefore, it is essential to develop and introduce new technologies that are compatible with current technologies. This is a common issue worldwide, and international standardization is essential to ensure that optical-fiber networks around the world are interconnected. Therefore, I have participated in the discussions at the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T), and since 2009, been leading discussions on international standardization of optical-fiber technology by serving as the chair (rapporteur) of the working group.

—All of these research activities are significantly contributing to society. To what specific level has your research progressed?

For about the past 10 years, we have been making world-leading achievements in the field of multi-core optical fibers, which has become a global trend. In 2017, by arranging 19 cores capable of 6-mode (channel) propagation in a cross-section of an optical fiber with a diameter less than 250 μm, we succeeded in arranging 114 spatial channels per fiber and creating a world-class ultrahigh-capacity-transmission optical fiber with mechanical reliability equivalent to that of current optical fibers. In 2018, we designed and prototyped a 10-mode, 12-core optical fiber as the world's highest-density SDM optical fiber. This fiber has more than 100 times the potential of current optical fibers in terms of both the amount of spatial multiplexing and spatial-utilization efficiency (spatial multiplexing per unit cross-sectional area) (**Fig. 2**).

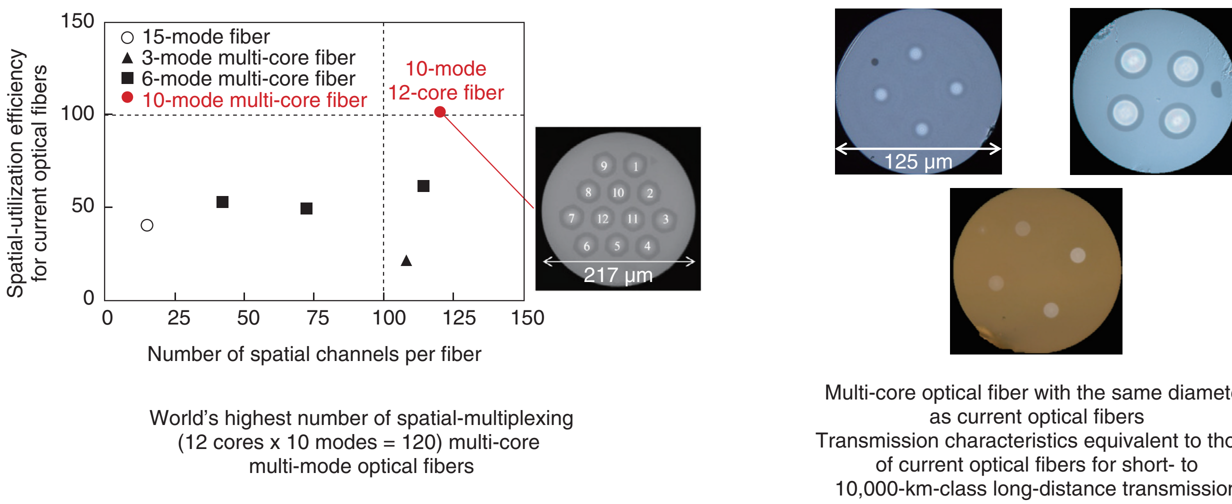

Fig. 2. Example study on a multi-core multi-mode optical fiber.

As the number of cores increases, the diameter of the optical fiber increases. The aforementioned diameter of 250 μm is almost twice that of current optical fibers, which reduces manufacturing efficiency. Given this drawback, we have also been attempting to increase the transmission capacity by fabricating multi-core optical fibers maintaining the same diameter as current optical fibers. Although further studies on, for example, mass production and connectivity, are needed for practical application of multi-core optical fibers, we have reported our research results concerning such fibers having excellent compatibility with current communication facilities and devices and can be applied to short- to 10,000-km-class long-distance transmission. As a result, we received prestigious awards, including the best paper award at the OECC (Optoelectronics and Communications Conference) in 2019.

Toward the implementation of the Innovative Optical and Wireless Network (IOWN), we aim to establish technology for four-core multi-core optical fibers having the same properties as current optical fibers by 2025. Then, by 2030, we hope to achieve a transmission capacity 125 times higher than current optical fibers by combining multi-mode and advanced optical-transmission technologies. Furthermore, we want to create the ultimate high-capacity-transmission optical fiber by integrating the holey fiber technology that we have been investigating.

Research themes can be found through hands-on experience

—Please tell us what you have been trying to do as a researcher.

What I have found to be very important and cherish is to approach various sources of information, such as papers and conference presentations, to find topics that interest me. Due to the COVID-19 pandemic, however, I get fewer opportunities for face-to-face discussions at conferences and fewer opportunities to stand around and chat during breaks, so I rely on email exchanges for stimulation. Through these exchanges, as well as by reading papers, I'm inspired by the research activities and perspectives of other researchers. Unfortunately, during online conferences and meetings, we are often momentarily distracted by the immediate tasks at hand and objects around our computers, missing out on important stimuli. Therefore, direct and on-site activities are the best.

One of the most important skills for researchers is the ability to determine what to aim for and what to investigate. To develop that skill, I have been trying to be aware of new things and challenge myself little by little. If you don't have enough flexibility, you can't come up with new ideas; therefore, I have been conscious of having enough flexibility to try and do a few different things, even if they seem useless at first.

From the lessons I learned above, I realize that investigating with your hands has the greatest benefit for researchers. This hands-on experience is very important because research themes and discoveries can be found in things that feel a little strange or uncomfortable.

Having been with NTT for 28 years, I have been working exclusively with optical fibers. The optical fibers in use today are outstanding and well designed, and optical-fiber technology has already been established in a sense. We have experienced an era in which we thought that we didn't need to pursue it any further. Nevertheless, from my many years of experience and intuition based on hands-on experience, I thought that optical-fiber technology would reach a limit, so I decided to pursue high transmission capacity. As it turns out, this prediction became a reality.

—What have you been keeping in mind regarding your research activities over the past 28 years?

Although I have been sticking to R&D on optical-fiber technology for communications, during my research activities, I have been keeping in mind the sense of "by-product," which means using the technology for other purposes. A little awareness and inspiration will gradually come to you if you are keeping it in mind. An NTT retiree, who was my senior concerning international-standardization activities, once told me, "Seize any opportunity by the back of the neck." Although Leonardo da Vinci said, "Seize fortune by the forelock," my senior used the phrase "the back of the neck." I felt the nuance in those words; that is, instead of constantly thinking about something, just somehow keep it in the corner of your mind and keep contact with it.

I often find that new ideas come to me at unexpected times, such as while eating or taking a bath. By keeping a research topic in a corner of your mind, you can find inspiration in a moment of everyday life. I feel this approach is connected to what I said earlier about ideas being born from flexibility by trying not to reduce too much waste. This approach especially works when you are conducting experiments, so if you are curious about something during an experiment, don't think of it as a detour, but find the time to investigate it. I feel that if you neglect this approach, your research will taper off. I want you to look at research activities from the viewpoints of a bug (micro), bird (macro), and fish (trend). Since we are working as a group, it would be best to leave the role of the bird's eye view to researchers who are somewhat senior and let the younger ones pursue their research with bug's eye view.

I was taught by my teachers and mentors that I was free to make proposals. I was always told that I should not think that I should not make proposals because I was a subordinate; rather, I should be involved in discussion by making proposals. I made an effort to think while listening to the experts and leaders in my group, and such discussions I had with them helped me a lot. Therefore, please try to make proposals and be engaged in discussions.

Have a strong sense of autonomy even though you are part of a team

—Such discussions with seniors and peers are unique to team-based research activities.

One of the major advantages of working in a team is that you can listen to the various opinions of your fellow team members. However, the division of tasks in the team sometimes becomes unclear, and that situation must be avoided. For instance, if it is not clear in regard to who is to be in charge of submitting a paper to a conference, you may not be able to be proactive or involved. Such autonomy is one of the attitudes that I hope young researchers will have as members of a team. Don't accept the results and numbers that come out of calculations or experiments without questioning. That is, originality lies in the perspective from which such results are examined, which will demonstrate your autonomy. Therefore, be extra aware of that fact.

I also believe that the key to pursuing originality and becoming a researcher with autonomy is to have interests and curiosity. Conducting an experiment just because your senior told you to do so indicates lack of interest and involvement. What researchers are required to do is not do what they are told to do; rather, interpret and process results while finding interest in what comes out. I think that is the most important requirement.

When I was younger, the group leader of an experiment that I was involved in would often return my reports back to me and say, "Look at it from various directions, up, down, left, right." It is quite difficult to interpret an experiment, but if you look at it from different directions then interpret it, you will discover something unexpected. Having said that, I still sometimes conduct an experiment without knowing what is going on, so I understand the feelings of young researchers. Also, like many of young researchers, I have experienced the feeling of shock by being told "no" by my seniors, so we seniors try our best not to say "no." Young researchers should keep trying and think that they are lucky if they have one success in ten tries.

—So young researchers are supported by this kind of encouragement from their seniors.

I believe that it is very important for researchers to be able to talk about their vision and directions—even if they belong to an organization. I joined NTT because I admired the mission of the Nippon Telegraph and Telephone Public Corporation, which was to widely spread information. I believe that it is of significance of delivering information via the transmission medium, i.e., optical fiber, and I want optical fibers to have a great impact on the people who use them. I hope that young researchers will have their own vision and directions.

Once again, I urge young researchers to conduct their research activities with a strong awareness of making proposals. Making proposals can be interesting. Even if one's proposal is rejected, I believe that pursuing the reasons for the rejection is one of the most exciting aspects of research. I'd like researchers to take pride in being the ones who are most familiar with the themes they are working on in their area—theoretically as well as experimentally—through their sweat, determination, and hands-on approach.

In my 28 years as a researcher, I have been able to get the bending loss-insensitive optical fiber we studied to be used, even if only partially, in NTT's network during the expansion of fiber-to-the home network. Unfortunately, since our seniors developed the optical fiber used in today's network, new optical fiber that surpasses it has not been introduced on a large scale. Even so, I remember being really happy that we were able to contribute to society, even if only partially. This experience has changed my mindset from pursuing research just because I'm curious about it to because it is useful to society. It also helped me develop a sense of by-product; that optical fibers could be used for purposes other than communications. I think that we now have a good opportunity to have such a mindset because IOWN has been announced and people are paying attention to information and communication technology, such as artificial intelligence and Internet of Things, and its peripheral fields.

Research is probably never complete. It will finish when you are satisfied. I think of it as a sound approach to think that research can last a lifetime. With that in mind, I want to continue to pursue optical-fiber technologies that connect all types of people, things, and events—through both R&D and international standardization—to support continuous development of optical-fiber networks.

■ **Interviewee profile**

Kazuhide Nakajima received an M.S. and Ph.D. in electrical engineering from Nihon University, Chiba, in 1994 and 2005. In 1994, he joined NTT Access Network Service Systems Laboratories, where he has been engaged in research on optical-fiber design and related measurement techniques. He is currently a senior distinguished researcher and group leader of NTT Access Network Service Systems Laboratories. He has been acting as a rapporteur of Question 5 of the ITU-T Study Group 15 since 2009. He is a member of the Institute of Electrical and Electronics Engineers (IEEE), Optica (formerly OSA), the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan and the Japan Society of Applied Physics (JSAP).

Research on Intelligent Reflector Control and Wireless Sensing for Intelligent Radio-wave Design Technology

Tomoki Murakami
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Abstract

As we move toward the era of the Innovative Optical and Wireless Network (IOWN), intelligent radio-wave design technology is expected to usher in a paradigm shift from provided transmission spaces to created transmission spaces. In this article, we speak to Distinguished Researcher Tomoki Murakami about the two technologies that underpin this technology.

Keywords: intelligent radio-wave design, intelligent reflector control, wireless sensing

The two technologies that underpin intelligent radio-wave design technology

—What exactly is intelligent radio-wave design technology?

Previous research on wireless technologies has generally focused on achieving high-speed communications in a provided wireless transmission space. In contrast, intelligent radio-wave design technology is a research concept that aims to maximize transmission quality and speed by changing the wireless transmission space itself in accordance with its surroundings, controlling the direction and strength of radio waves.

Using our smartphones as an example, we have thus far improved mobile terminals and base stations to aim for even faster communications by making use of the radio waves that are constantly transmitted from base stations to mobile terminals. In contrast, the intelligent radio-wave design technology being proposed can enable us to provide a better Internet infrastructure and networked environment by recognizing the wireless environment of the city itself in real time and dynamically changing the direction of the radio waves using devices scattered throughout this space, thereby allowing radio waves to reach places they could not reach before. As data traffic increases and as we enter into the era of Internet of Things and the Innovative Optical and Wireless Network (IOWN)—where not only people, but things also communicate—communications is becoming

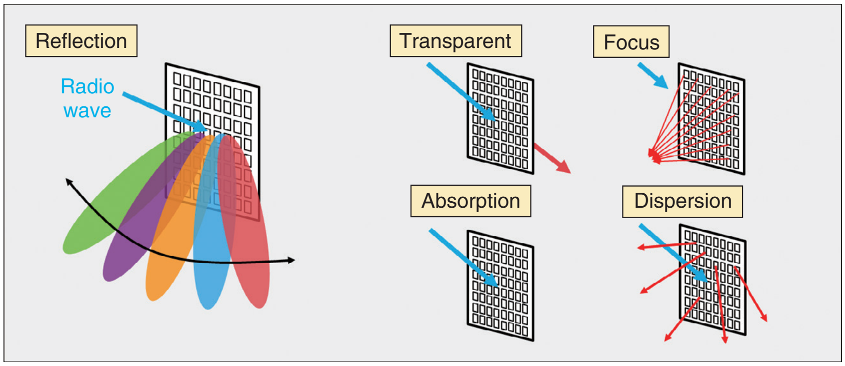

Fig. 1. How an intelligent reflector works.

increasingly important. We have therefore established a group whose main mission is to establish intelligent radio-wave design technology, aiming for a high-quality, connected world, even when networked environments change.

There are various ways of designing an intelligent radio wave, for example, having radio waves received and their signals processed at relay stations. However, today I would like to tell you about two underlying technologies that I am involved in: intelligent reflector control and wireless sensing.

—What exactly is intelligent reflector control?

Reconfigurable intelligent surfaces (RISs) are reflectors made from special materials that change the electrical characteristics of radio waves. Their reflective characteristics such as their angle of reflection and transmissivity can be altered by electronically controlling each element. When reflecting light with a mirror, the angle of incidence light is equal to the angle of reflection light. But with RISs, the direction of the reflected radio wave can be changed as the angle of reflection can be controlled at will.

As an example, this means radio waves can be made to reach places they could not previously reach with conventional reflectors due to shadows cast by obstacles. It is also now possible to focus radio waves to specific points to improve transmission quality. In addition, we can now also transmit radio waves directly through and behind reflectors, absorb them so that they do not reach anywhere, or disperse them over a wide area, as detailed in **Fig. 1**.

We are conducting research on the technologies that control these RISs. We have been conducting a joint experiment with NTT DOCOMO on the effect of RISs on 5G (fifth-generation mobile communications system) radio waves, which we announced in a press release in November 2021 [1].

At present, we are focusing our research and development on collaborative-control technology for multiple intelligent reflectors, with the aim of further improving transmission quality.

—What is wireless sensing?

In order to design intelligent radio waves, it is essential to understand the shape of the real space and its radio environment—in other words, sensing technology is essential. It visualizes information acquired through sensing and previously collected big data, analyzes it using machine learning, and then feeds this all back to RISs that alter the space.

Since 2020, I have also been working at NTT Network Innovation Laboratories, where I am conducting research into spatial recognition through sensing that combines various types of media, such as cameras. Within this, wireless sensing is comparatively easy to achieve using specialized equipment and dedicated apparatus. However, our research aimed to do this in an affordable way, and to obtain various kinds of information using existing wireless apparatus. The key is using such information for purposes other than communications. From signal strength, we can obtain information such as the location of mobile terminals, whether there are people around and how crowded it is, and whether a door is open or closed.

We actually set up a Wi-Fi router in our meeting room, first had a system learn what the room was like when people were in it, and then took measurements, and we found that we were able to detect with a high accuracy of around 95%. As we move toward the

IOWN era, we hope that we will be able to develop new markets by expanding our wireless systems to areas other than communications.

Intelligent radio-wave design technology will usher in a paradigm shift

—What are your plans for future research?

Intelligent reflector control has currently only been evaluated indoors in a single environment. Going forward, we would like to roll it out outdoors and test its effectiveness in an actual environment. Compared to indoors, where there are fewer moving objects, the outdoor environment changes a lot with many moving objects, such as vehicles that can affect the radio waves, so we expect that control will be difficult.

At present, we are experimenting with a single reflector surface, but we would like to do testing on the use of multiple reflector surfaces as well. In order to obtain information from multiple reflector surfaces and control them individually, we need to consider what to do about control signals. While there are still a number of issues to be resolved, we believe that we will be able to achieve even greater results in terms of transmission quality.

Furthermore, I want to get started on the development side of our research, for example implementing it at an actual base station. In the future, we hope we will be able to provide a high-quality, uninterrupted environment through the collaborative control of intelligent reflectors positioned in various places.

We have already paved the way for the implementation of wireless sensing, and are now considering the possibility of introducing sensing functionality to existing base stations. There are always obstacles to overcome when creating something new, but there are no such obstacles if you use something that already exists, so testing can be done relatively quickly. By finding and calling attention to use cases over the next few years, we hope we can create a world in which sensing functionality becomes entirely commonplace.

—What kinds of possibilities will intelligent radio-wave design technology unlock?

In the IOWN era, as services and applications become more and more diversified, the requirements of wireless networks will also become more diverse. They will need to be more reliable and have lower latency, rather than simply having higher speeds. The implementation of intelligent radio-wave design technology will have various effects such as higher data transmission speeds, increased transmission coverage, reduced latency, and lower packet loss. This will be a paradigm shift from provided wireless transmission spaces to wireless transmission spaces that we create. I truly think this has incredibly vast potential.

Currently, some environments cause frustrations such as connection difficulties and time lag, but I believe that this will no longer be the case in the future, as we will be able to freely use wireless transmissions unbound by environment or application. I believe that this technology will form a foundation for providing better services to customers.

—Is there anything you would like to say to young researchers and future business partners?

NTT Access Network Service Systems Laboratories not only creates new technologies, but also places a great deal of importance on the commercialization of these technologies, which means providing them to the world in the form of specific products and services. It would make me happy and give me great satisfaction to be able to show something to my own children and tell them that their father made it.

In terms of external partnerships, I think the most important thing is that we have been able to conduct joint research on sensing technologies. Initially, we had the wireless communications technology, but we lacked knowledge and expertise when it came to sensing. Therefore, we collaborated with companies in different fields on this by having them use the wireless sensing equipment we developed and conduct research and development of various technologies side-by-side, which really helped propel our efforts forward. As we created a system that could measure radio waves using commercially available equipment, we have been able to collaborate with many joint research partners, and as a result, we have been able to significantly expand the scope of this technology.

We believe that conducting joint research with companies in different fields, rather than in the same communications field as us, gives us greater potential and greater effectiveness in terms of the new things that can be created. We have a diverse range of research collaborators in fields such as information processing, agriculture, materials, and heavy machinery, and we would like to continue collaborating in a variety of areas in the future. With toys as an example, there are things like radio-controlled cars that use wireless technology in a very simple way. However, there are not many products that use the latest wireless technologies. There may be some issues in terms of cost, but I believe that even more fun and interesting products could be created.

I would like those involved in research at their company to be aware of the fact that some research and development is unique to their company. At universities, I think academics are involved in some really cutting-edge research in certain fields. However, I think companies need to focus on how they can contribute to society by actually providing tangible products.

I would like to encourage any of our future business partners to utilize our basic technologies for IOWN by conducting research and development together with us. We will be working hard to create new products and services, and are looking forward to working together.

Reference

[1] Press release issued by NTT and NTT DOCOMO, "NTT and NTT DOCOMO Trial First Use of User-tracking Metasurface Reflector for Extreme Mobile Coverage in Current 5G and Coming 6G Era," Nov. 12, 2021.
https://group.ntt/en/newsrelease/2021/11/12/211112b.html

■ **Interviewee profile**

Tomoki Murakami joined NTT in 2008 as a master's graduate, working at NTT Network Innovation Laboratories. In 2015, he moved to NTT Access Network Service Systems Laboratories and subsequently obtained his Dr.Eng. from Waseda University. He was awarded the IEEE (Institute of Electrical and Electronics Engineers) AP-S Japan Chapter Young Engineer Award in 2014 and the ARIB (Association of Radio Industries and Businesses) Radio Achievement Award (The Prize of the Minister of the Ministry of Internal Affairs and Communications) in 2020 while working at NTT Network Innovation Laboratories.

Software Technologies in the Data-centric Era

Seiji Kihara and Hiroyuki Tanaka

Abstract

With the arrival of a *data-centric society*, where various types of value are created from real-world data, demand for system infrastructure and software-development methods as business evolves has risen to an even greater level. In this article, we introduce various technological challenges and the efforts of NTT laboratories, particularly the NTT Software Innovation Center, in developing an information-processing infrastructure for the data-centric era to meet the requirements of business evolution and support a data-centric society.

Keywords: information-processing infrastructure, data sharing, software

1. Situation surrounding information-processing infrastructure

Processes for solving real-world issues by using a variety of real-world data are taking on greater importance. There is no shortage of examples of the application of such processes. For example, in the manufacturing industry, factory operational data can be used for forecast management and predicting equipment failure. In the retail industry, weather data can be used to forecast supply and demand and customer behavior data can be used to plan marketing activities and design store traffic flow. We call this process of creating value from data *data valorization*. Besides the intensification of competition between companies and the worsening of environmental and social issues, COVID-19 has forced society to transform into a remote-work society. This state of affairs is forcing society as a whole to undergo digital transformation, and even greater expectations are being placed on data valorization. We believe that such an environment will bring about a *data-centric society* in which value is created from data for all aspects of life in society, such as making decisions and predicting the future. In a data-centric society, the role of the information-processing infrastructure, which provides the foundation for sharing and analyzing vast amounts of diverse data, will become even more critical.

Reviewing the history of technological progress to date, we see that the information-processing infrastructure has evolved steadily. In terms of system infrastructure, processor performance has advanced as a result of first boosting single-core central-processing-unit performance through semiconductor miniaturization then evolving to a multi-core processor architecture. The speed and sophistication of the entire system has advanced due to performance speed-up and scaling as a result of the evolution from single-server processing to distributed and parallel processing. NTT has proposed the concept of the Innovative Optical and Wireless Network (IOWN) [1, 2], which, in addition to hardware and network advancements, calls for improvements in software supporting these technologies—in other words, improvements in system-infrastructure technology. In terms of software-development methods, in addition to the waterfall development model, which is well-suited when large-scale, high-quality software such as mission-critical software is required, other development methodologies have become widely adopted. These approaches include agile development, a method well-suited for web applications, which require rapid development for immediate availability and reiterations for improving usability. New software-development technologies that can support accelerating business transformation are thus

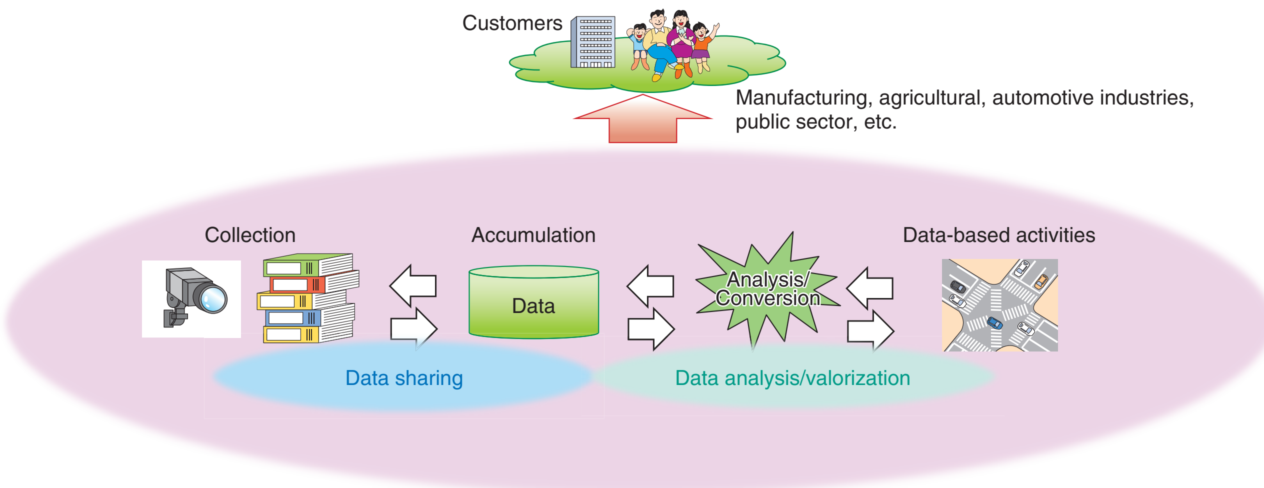

Fig. 1. Value chain in a data-centric society.

in demand.

Against this background, the NTT Software Innovation Center (SIC) is engaged in the research and development of system-infrastructure and software-development technologies that can support a data-centric society and business evolution. Through collaboration with each NTT laboratory, which specializes in related technologies, we are working to develop a future information-processing infrastructure based on IOWN.

2. Information-processing-infrastructure technologies for supporting a data-centric society

The broad flow of data valorization in a data-centric society is shown in **Fig. 1**. First, data related to real-world things and events in various real-world places, such as sensing data and log data, are generated, collected, and accumulated. Next, activities to apply these data to real-world problems are carried out by analyzing and converting these data. In many cases, the data about the real world changed by such activities are repeatedly collected. By reiterating the cycle of data collection, the real world is gradually improved and real-world changes are continuously tracked. With this process of applying feedback to the real world using data as evidence, it is possible to steadily change the real world in a positive direction and provide value to customers in a variety of domains.

We are engaged in the research and development of the following information-processing technologies to support the value chain of such a data-centric society.

(1) Disaggregated computing technologies

In a data-centric society, high-speed processes are required for all aspects of data handling, from data generation to transport, processing, and delivery, to valorize the vast amounts of data generated and used in a data-centric society. NTT has proposed IOWN and is also advancing research activities to achieve a smart society. These goals share in common the demand for high-speed, broadband networks and high-performance computers. To develop such a computer, NTT has proposed the concept of an architecture called *disaggregated computing*, which makes maximum use of photonics-electronics convergence technology (please see “Disaggregated Computing, the Basis of IOWN,” NTT Technical Review, July 2021 [3]). We are cooperating with the NTT Network Innovation Center and NTT Device Innovation Center, which operate as part of the NTT IOWN Integrated Innovation Center (established in July 2021 [4, 5]), especially in the area of system software (an example of this effort is introduced in the NTT Technical Review article “Memory-centric Architecture for Disaggregated Computers” [6] in the same issue above).

(2) Data-sharing technologies

To truly use data produced in a data-centric society, it will be necessary to combine data sets separated by geography and networks as well as cross-multiply data sets across organizational and state boundaries. This cross-multiplication requires not only high-speed networks and high-performance computers but also data management and processing in line with the data's generation and accumulation conditions, lifecycle, and permissions based on data owners' agreements. Our effort to solve these challenges is introduced in the feature article "Next-generation Data Hub for Secure and Convenient Data Utilization across Organizational Boundaries" [7] in this issue. This effort is being carried out in partnership with NTT Social Informatics Laboratories (established as part of the reorganization of NTT laboratories in July 2021 [8]).

(3) Data analysis/valorization technologies

To create value from data, computers and information-sharing systems are not enough. We must confront specific problems in each value-producing domain and find appropriate combinations of data and analytic methods for the diverse data sets and methods that can be procured—in short, to formulate the problem. This undertaking requires grounding in statistics and machine learning and understanding of each domain, and, along with these capabilities, support from tools and platforms. Because these capabilities and technologies are needed in every type of field, many NTT laboratories are engaged in their development, with efforts especially centered at NTT Computer and Data Science Laboratories (established as part of the reorganization of NTT laboratories in July 2021 [9]). At SIC, we are working on a processing infrastructure that carries out high-speed conversion of data to value on the basis of problem formulation. A specific example of this effort is introduced in the feature article "High-resolution Multi-camera Analysis Infrastructure to Support Future Smart Cities" in this issue [10].

(4) Software development technologies

In a data-centric society, because businesses and services will need to evolve at an even faster tempo, conventional methods of software development will eventually hit a limit. We are thus engaged in the research and development of technologies to achieve new rapid software development. These technologies include artificial intelligence (AI) that replaces or transcends a portion of human software-development tasks and allows AI and humans to work together. A specific example of our effort is introduced in the feature article "Test-activity Analysis for Efficient Iterative Testing" [11], which discusses technologies to improve the efficiency of regression testing as software functions are reiteratively added or improved.

3. Going forward

To achieve a future information-processing infrastructure that meets the requirements of business evolution and supports a data-centric society, we must address the variety of challenges described in this article. On the basis of IOWN, we are aiming to establish each technology as early as possible in collaboration with partners in various industries and experts in academic and industrial fields.

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Next-generation Data Hub for Secure and Convenient Data Utilization across Organizational Boundaries

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Abstract

In a data-driven society, where balancing both economic development and solving social issues is anticipated, utilizing a variety of data across the boundaries of companies and organizations will be necessary. However, there are many challenges related to the handling of sensitive data and algorithms and acquiring desired data from diverse data sets in different companies and organizations. Data utilization across organization boundaries thus has not been widely carried out. In this article, we introduce our next-generation data hub and its key technologies for addressing these challenges to allow data to be used securely and conveniently across organizations.

Keywords: data sharing, data hub, data sandbox

1. What is a next-generation data hub?

As seen in smart cities and cross-enterprise digital transformation, efforts have begun to create new value and solve social issues through data sharing and utilization across companies and organizations. However, the following challenges must be addressed to expand such efforts not just to a limited part of society but to all of society.

- It is difficult for data users to find data that match the desired purpose from among the vast amount of data gathered and managed respectively by each company; it is also difficult for them to acquire such data quickly when needed.
- It is difficult for data providers to appropriately control the use of their valuable data. It is also difficult for them to understand the range in which their data are distributed and the track record of their use.
- Data or data-analysis-algorithm providers are also especially concerned about leakage of sensitive information due to their use for non-intended purposes when other companies are allowed to use data providers' sensitive data or data-analysis algorithms containing valuable information.

To address these challenges, we are engaged in the research and development of a next-generation data hub. This data hub is a data-sharing infrastructure that maintains governance of data by data providers while allowing data users to quickly and efficiently obtain necessary data kept at multiple locations. It allows data to be used securely and conveniently across the boundaries of companies and organizations.

There are three main components of our next-generation data hub (**Fig. 1**):

(1) Virtual data lake: It enables efficient data search and acquisition by virtually integrating data kept in multiple companies and organizations.

(2) Data broker: It enables efficient sending and receiving of data between multiple locations.

(3) Data sandbox: It enables execution of data and

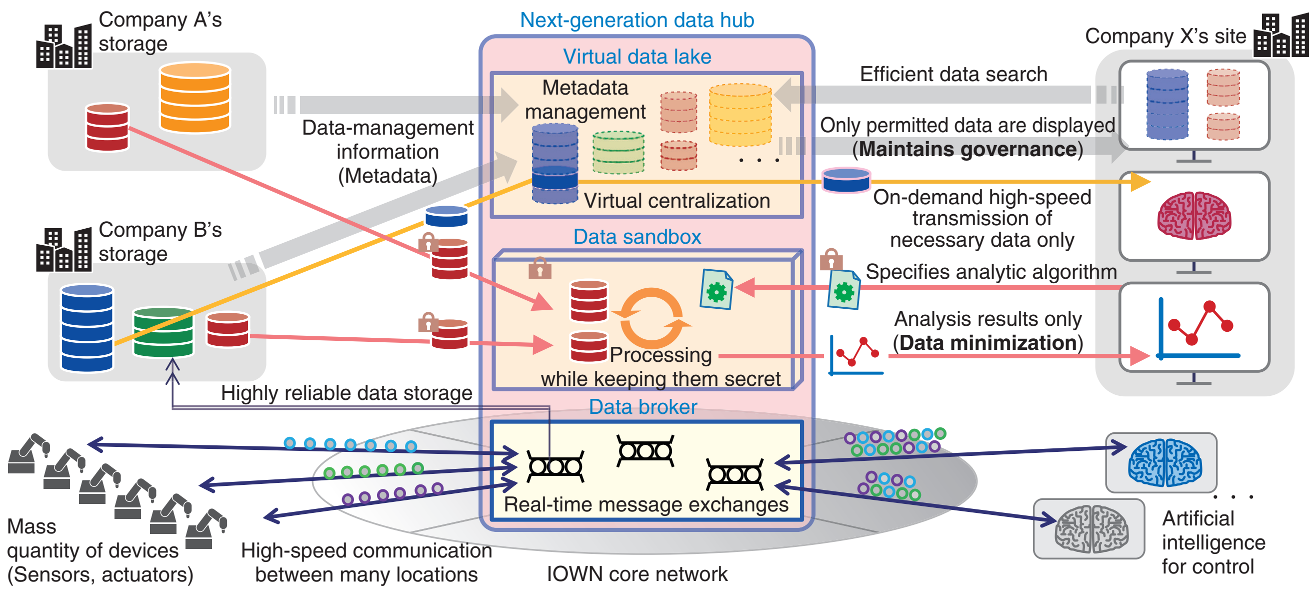

Fig. 1. Next-generation data hub.

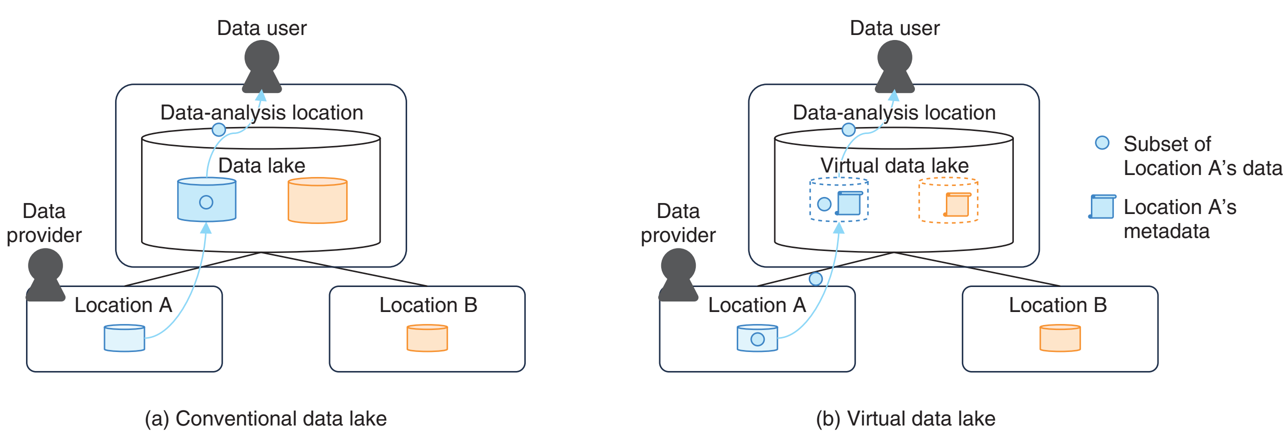

Fig. 2. Data-sharing models.

algorithms between companies while keeping them secret from each other.

We explain the problems to be solved with each component and their solutions in the following sections.

2. Virtual data lake

When using data that exist in multiple organizations and locations with the conventional model (as shown in **Fig. 2(a)**), data generated in each location are aggregated into a single location to create a vast data lake. Each user accesses the lake to use the data. However, this model has general problems such as the need to copy entire data sets, even when data users actually use just a small portion of the data. In addition, data providers face the problem of losing data governance because a large number of copies of their data are generated. It is thus difficult to conduct various analyses by sharing data between companies or organizations.

We are thus engaged in the research and development of a data-infrastructure technology called virtual data lake. This technology enables the data in various locations to be used without the need to aggregate them into a single location.

As shown in **Fig. 2(b)**, a virtual data lake does not collect data. Instead, it virtually aggregates and centralizes data by collecting their metadata[*1]. This makes it possible for data users to efficiently obtain the necessary data on demand for analysis and processing. For data providers, this technology makes it easy to maintain governance of their data by allowing them to always manage master data at their locations and providing data to data users upon request via the virtual data lake.

We are implementing this data lake from two perspectives: (i) data discovery and utilization, which is related to how to efficiently discover and use data necessary to meet data users' purposes from vast amounts of data with different formats and quality due to different acquisition histories, and (ii) data management and delivery, which asks how to efficiently manage ubiquitous data generated and growing daily in different locations, and how to deliver data to data users in an always usable condition and at the appropriate time. Next, we explain our efforts to address challenges associated with these two perspectives.

2.1 Data discovery and utilization

To enable data users to discover data they need from a vast amount of data, we assign and manage metadata, which explain data in detail in a unified, rule-based manner.

Some types of metadata, such as the semantic information of data, are assigned in advance by the data provider, while other types, such as format or quality information of data, are assigned automatically. By using metadata, data users can search data flexibly with various conditions. This makes it easy for them to narrow down to the data they need for achieving their purposes.

Metadata on the relationships between different data or the provenance of data—information on origin, distribution route, and processing executed for them—are also assigned and managed. Metadata on relationships between data make it easier for data users to find the data they need by traversing relevant data, even if they have just a vague clue about what to look for. Metadata on provenance of data make it possible to confirm, for example, that the data have not been improperly processed or that they have an unknown or suspicious origin. This enables data users to determine the data's reliability.

2.2 Data management and delivery

Managing dispersed data in their locations efficiently without aggregating them and enabling them to be obtained on demand presents several challenges. We first present our efforts to efficiently and remotely understand and manage the latest statuses of data, which are generated and updated daily at various locations. We then present our efforts to improve response time from data request to receipt so that it approaches that of a single data lake in which data are aggregated.

To allow data at all locations to be available to data users at any time, information on events in each location, such as data creation, update, and deletion, are collected with low latency and managed as metadata. By using up-to-date metadata, data users can handle the data as if they exist locally. For example, they can view a list of latest file information and issue a request to retrieve a file's content.

To ensure that the response time from a data request by a data user to its return is not so long as to present a practical use problem, we will also deploy a data format that carries out incremental data delivery and a caching mechanism within the virtual data lake. These solutions make it possible to suppress an increase in processing time due to data transmission in processes that repeatedly use the same data such as machine learning. We are also developing a prefetch function that dynamically caches data on the basis of the data's access pattern and frequency and a function for push-type distribution of data from each data location to the virtual data lake. We are designing and developing functions so data users and providers can plug in their algorithms into the virtual data lake according to their requirements.

3. Data broker

With the development of smart factories and connected vehicles, large amounts of sensors and terminals are required to be connected in one single network, where messages are exchanged for monitoring and control of factories or vehicles. For accurate monitoring and control, it is necessary to collect data from terminals and send feedback to terminals reliably in an extremely short amount of time. Therefore, we are developing a new broker technology to enable low-latency and high-reliability exchanging of

*1 Metadata: In this article, metadata refer to "data for explaining data." Such metadata include information about the data's location, creator, and format.

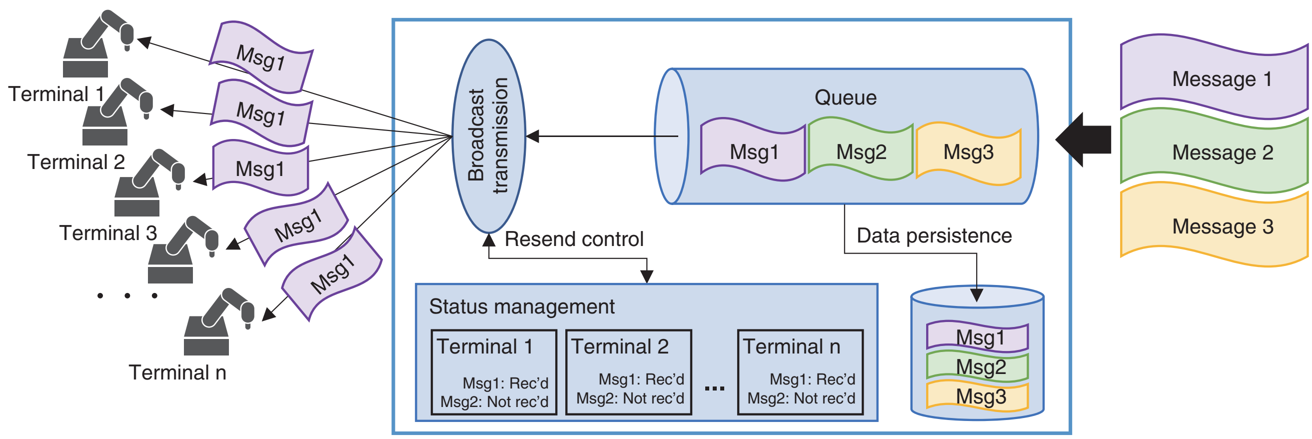

Fig. 3. Persistence and resend mechanism.

messages among huge quantity of terminals.

Conventional broker technologies prioritize one of two aspects: (i) efficient transmission of the same information to a large number of terminals, in which case reliability is sacrificed as message persistence is not ensured and resending of messages is not carried out, or (ii) reliable transmission, in which case transmission to a large number of terminals cannot be supported. It is difficult to support requirements for both aspects at the same time. To achieve both sets of requirements, a challenge is the resend process for messages that are not received by terminals. To resend messages, it is necessary to record the transmission status of every message for each terminal, and managing statuses becomes extremely costly when a large number of terminals are connected in a network. As a result, transmission delays occur due to insufficient computing resources of brokers. We are working to address this challenge by improving transmission protocols and status-management algorithms (**Fig. 3**).

By accumulating these efforts, we will achieve a new data broker that allows low-latency, high-reliability message exchanges between a large number of terminals.

4. Data sandbox

4.1 Background

As stated above, despite the expectation that new value will be created by analyzing sensitive data with an algorithm held by different companies, companies have not collaborated much with one another due to concerns about leakage of their data and algorithms.

A simple method for analyzing data with an algorithm without disclosing data or the algorithm to each other is to leave data and the algorithm to a third party (platform provider). The platform provider is asked to return only the analyzed result. With this method, there is no need for companies to disclose data and an algorithm to one another. However, the remaining issue is that data and an algorithm are disclosed to the platform provider.

We are researching and developing a data-sandbox technology that, while on the basis of the model of the platform provider performing computation on behalf of data providers and algorithm providers, enables the analysis of data with an algorithm to be kept secret from the platform provider. We seek to achieve utilization of data and algorithms such as the following with this technology.

- The ability for competing companies to bring together data, process them, and share the results among themselves. None of the companies disclose their own data and algorithms to others or the platform provider.
- The ability for a company to analyze its valuable data by using a secret analysis program developed by another company and obtain analytic results. None of the companies disclose original data or analytic programs to each other or to the platform provider.

4.2 Technological challenges and approaches for solutions

To enable data utilization as described above, the following issues must be addressed.

- Issue 1: Unauthorized execution of algorithms

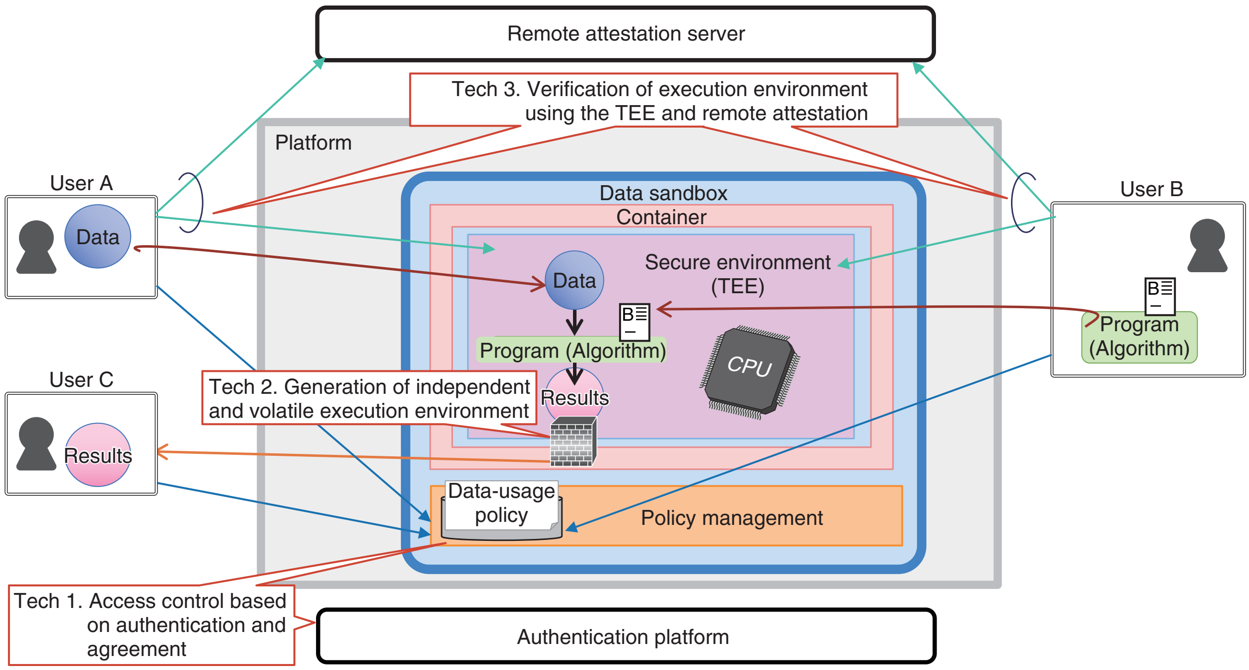

Fig. 4. Data-sandbox technology.

by spoofing, which results in the spoofer illegally acquiring the original data and results

- Issue 2: Leakage of original data and results due to execution of faulty algorithms
- Issue 3: Unauthorized acquisition of original data and algorithms by the platform provider

Our data sandbox addresses these issues by combining the following technologies (**Fig. 4**).

Technology 1: Authentication and agreement-based access control

The data sandbox authenticates users (data and algorithm providers and users of result data) to prevent spoofing. It also controls access to original data, algorithms, and result data in accordance with agreements (data-usage policy) set in advance by users to prevent unauthorized execution of algorithms and acquisition of data.

Technology 2: Creation of volatile and independent execution environment

The data sandbox creates an independent execution environment for each data-usage policy agreed upon by users. Access to the outside from this execution environment is also restricted. This prevents algorithms from taking data to the outside in violation of the data-usage policy. Furthermore, the execution environment is deleted after processing of an algorithm is completed, preventing the leakage of data and algorithms.

Technology 3: Verification of the execution environment by applying TEE and remote attestation

The Trusted Execution Environment (TEE)[*2] and remote attestation[*3] are technologies for preventing operators and administrators of the execution environment, such as the platform provider, from accessing data and algorithms. By applying these mechanisms, the data sandbox allows users themselves to verify that the data and algorithms set into the execution environment are those agreed upon by the data-usage policy and that the execution environment being used is generated using the TEE, with the data and algorithms being kept secret. Applying these mechanisms prevents the platform provider from

*2 TEE: Trusted Execution Environment (TEE) is an isolated execution environment architected such that the memory region is encrypted by the central processing unit (CPU) so that administrative users of an operating system cannot read the content of the memory. This mechanism has been used mainly in mobile terminals and embedded devices. However, it has been incorporated into many server CPUs by manufacturers such as Intel and AMD.

*3 Remote attestation: Function provided by CPU vendors as a method for users to confirm the authenticity of the TEE. By obtaining information about the TEE's configuration and having the CPU vendor attest to its authenticity remotely via the Internet, users can verify that the TEE has been created using the genuine functions provided by the CPU vendor and it was not falsified.

accessing data and algorithms while allowing users to obtain results that come from analyzing data with an algorithm.

5. Going forward

In this article, we introduced the main components of our next-generation data hub that we are researching and implementing: virtual data lake, data broker, and data sandbox. Our next-generation data hub will enable safer, more secure, and more efficient data sharing. It will thus foster the creation of new value and solutions for social issues through the mutual use of highly confidential data and algorithms across companies and organizations, which had been considered difficult to date. We will further accelerate the research and development of these elemental technologies and evaluate them with partners to contribute to achieving a data-driven society as early as possible.

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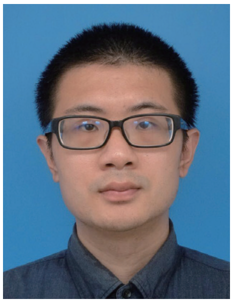

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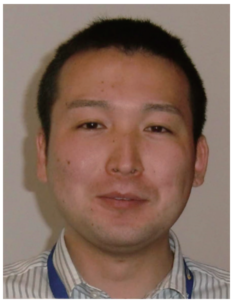

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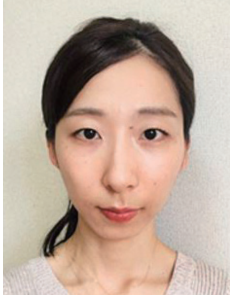

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High-resolution Multi-camera Analysis Infrastructure to Support Future Smart Cities

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Abstract

In the IOWN (Innovative Optical and Wireless Network) era, smart cities will be built on a cyber-physical system (CPS) that makes all information in the city valuable and accessible. In this article, we introduce an artificial intelligence (AI) inference infrastructure that can efficiently process high-resolution, multi-camera images to support an urban-scale CPS. This infrastructure is based on the concept of event-driven inferencing to significantly reduce the processing loads and energy consumption of AI-inference processing executed with the infrastructure. The basic techniques of model cascading and inference resource sharing are discussed in the article.

Keywords: IOWN, smart city, AI

1. Smart city and cyber-physical system

When you hear the term smart city, what kind of city comes to mind? According to the definition by the Ministry of Land, Infrastructure, Transport and Tourism [1], a smart city is "a sustainable city or district that is managed to achieve total optimization while utilizing new technologies such as information and communication technology (ICT) to address the various issues facing the city." The Nomura Research Institute's definition [2] more specifically defines a smart city as "one that collects and integrates a variety of data, such as environmental data, facility operation data, consumer attributes, and behavioral data, through sensors, cameras, smartphones, and other devices installed throughout the city, and uses artificial intelligence (AI) to analyze the data, as well as remotely controlling facilities and equipment as necessary, with the aim of optimizing urban infrastructure, facilities, and operations, and improving convenience and comfort for businesses and consumers." Both definitions aim to achieve total optimization by using ICT technology to manage and operate a city. One concept, the goal with which is to achieve optimization by processing information from the real world, is the cyber-physical system (CPS). As shown in **Fig. 1**, a CPS takes information from the real world (physical), passes it to a virtual space (cyber), analyzes it through computing, then feeds back the results of the analysis to the real world to optimize real-world operations.

What will happen when reality becomes programmable, i.e., the *softwarization* of reality? In fact, the softwarization of reality is already happening everywhere. Take the telephone, for example. In the past, a telephone was a box with a handset and a dial, and cell phones, which have become smaller and more wireless, were initially just terminals to connect remote locations. However, the advent of the smartphone, a softwarized phone, changed the world. Physical buttons became icons on touchscreens, which eventually transformed freely into all sorts of palm-sized interfaces (phones, calculators, books, cameras, etc.). E-books and digital cameras are examples of books and cameras that have been softwarized. As a result, the static, one-way interface of

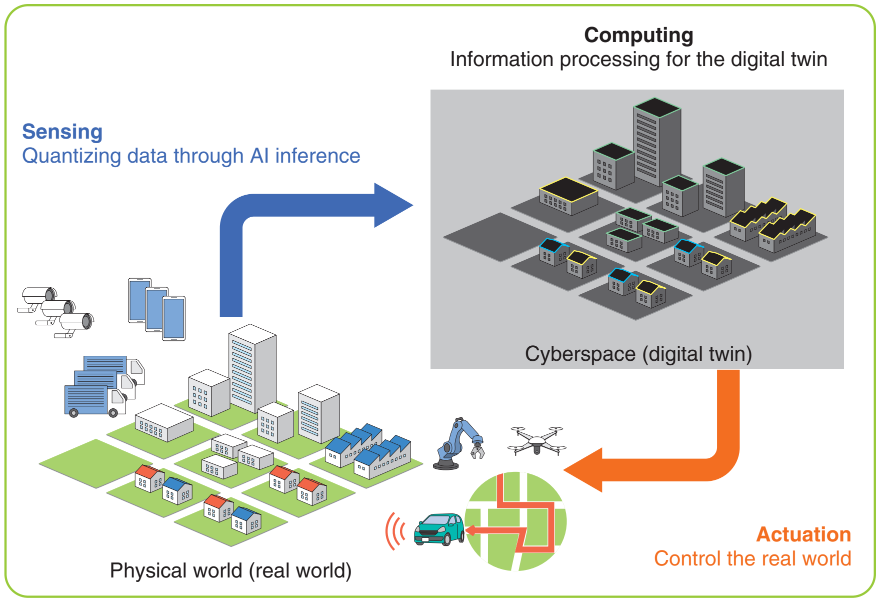

Fig. 1. A CPS.

the past has been transformed into a dynamic, interactive one, and the information presented can be personalized and recommendations can be made to suit the recipient. This yields dramatic improvements in convenience and comfort.

Let us return to the topic of smart cities. Yes, a smart city is a *softwarized city*. The building blocks of a city had been physical such as concrete buildings, metal signs, and transportation systems. In a smart city, however, buildings will be smart buildings controlled by a building management system, signs will become digital signage, and transportation will have smart mobility such as connected cars, all of which are programmable. If cities become software-driven, always-crowded roads may be replaced by smart roads that optimize lanes and speed limits to optimize traffic conditions, and buses that seldom come may be replaced with self-driving cabs that stop in front of you the moment you want to go somewhere.

By constructing a city-scale CPS and using it to promote the softwarization of various urban services, we can expect dramatic changes and improvements in convenience and comfort on a city scale, similar to what happened when telephones became smartphones.

2. The key is to reduce the processing loads of and energy consumed by AI-inference processing

The question is, then, whether a city-scale CPS, which is the foundation supporting smart cities, can be readily implemented. A CPS consists of three major steps: sensing, computing, and actuation, and a variety of research is currently underway for each of these steps. The NTT Software Innovation Center (SIC) is developing an AI-inference infrastructure for sensing and computing. Sensing in a smart city is executed by analyzing a large amount of stream data continuously generated from cameras and various sensors placed throughout the city, as well as from connected cars and smartphones in the city, using inferencing based on deep learning (so-called AI inferencing) and converting the data into meaningful information. AI inferencing is also essential for reconstructing information in the form of a *digital twin* on a computer system and for computing the feedback that yields the desired results in the real world.

Traditionally, AI inferencing is a process that incurs excessive computation loads. Our solution is to develop a combination of stream merger and GPU (graphics processing unit) offloading to improve efficiency and capacity. However, to achieve the Innovative Optical and Wireless Network (IOWN) concept of implementing AI systems that can capture events

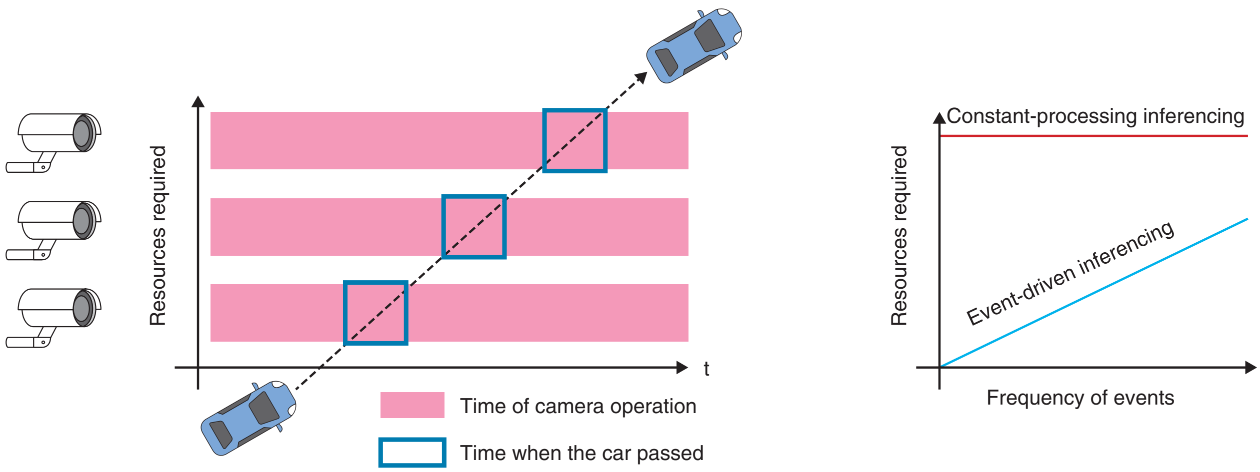

Fig. 2. Concept of event-driven inferencing.

on a scale that cannot be handled by humans and analyze and make decisions at a speed that exceeds that of humans, it is necessary to increase the resolution and frames per second (FPS) of input data and support the sheer number of cameras and sensors that the city scale demands [3]. In general, the processing loads of and energy consumed by AI inferencing are proportional to the amount of data to be analyzed, so an explosive increase in the amount of input data leads directly to an explosive increase in processing loads and energy consumption. To achieve a city-scale CPS that supports smart cities in the IOWN era, it is necessary to reduce the processing loads and energy consumed to a sustainable level.

3. Concepts and elemental techniques of event-driven inferencing

To reduce the processing loads and energy consumption described above, we are developing the implementation concept of AI inferencing of stream data called *event-driven inferencing*. Event-driven inferencing makes the processing loads incurred by AI inferencing proportional to the amount of valuable information rather than the amount of input data (**Fig. 2**).

Conventional constant-processing AI inferencing treats all frames as equally important, so the processing loads and energy consumption depend on frame characteristics (resolution, FPS, number of streams, etc.). Therefore, increasing the resolution, FPS, and number of cameras and sensors deployed will directly increase the processing loads and energy consumption. At first glance, this may seem unavoidable, but consider the mechanism of human cognition. Humans use event-driven cognition, which lightly monitors the whole field of perception, and when a significant event (such as a sudden movement or sound) is noticed, closer attention is paid to that event. In this case, the processing loads and energy consumed for cognition depend on the number of objects in the field of perception important to the individual, i.e., the amount of valuable information. Event-driven inferencing involves the same principle to make AI-inferencing implementation practical.

There are several possible approaches to achieving event-driven inferencing. A typical approach is model cascading. Model cascading analyzes the same frame in multiple steps, which is detailed in the next section. Other approaches include temporal control and spatial control. In temporal control, the analysis parameters of subsequent frames are controlled on the basis of the analysis results of the previous frame. For example, in temporal control, the analysis is executed at 5 FPS in normal operation, and only when a person is detected, the frequency of analysis is increased to 15 FPS. Spatial control involves the topology of cameras and sensors and uses the analysis results of one input source to control the analysis parameters of other input sources. For example, “Analyze the camera images in the area only where a person is detected by the camera at the entrance of the monitored area.”

To actualize this concept, SIC is investigating model cascading and inference-resource sharing.

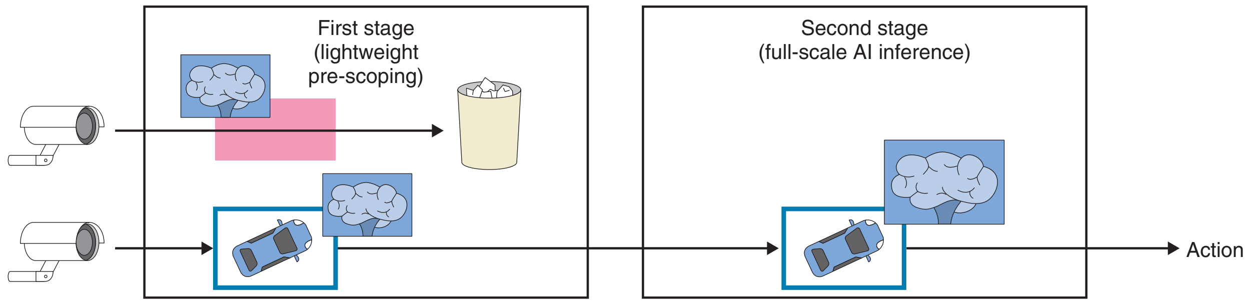

Fig. 3. An example of model cascading using a pre-scoping model.

4. Model cascading

To achieve event-driven inferencing, events must be detected in some way. Model cascading combines a lightweight pre-scoping model for event detection in the first stage with an AI-inferencing model for full-scale analysis in the second stage; the AI inferencing model is activated in the second stage only when an event occurs, thereby reducing overall processing loads (**Fig. 3**). There are several variations of pre-scoping [3], including one that uses event detection to winnow the frames sent to the second stage, one that uses a lighter, lower-resolution model to infer the same task as the second stage and sends it to the second stage only when the confidence in the processing result is low, and one that divides AI inferencing into separate parts and uses the first part for pre-scoping and sends the intermediate output to the second stage. The optimal configuration will vary depending on the use case and hardware configuration.

5. Inference-resource sharing

Inference-resource-sharing technology is needed when the valuable information-dependent approach is used for processing in event-driven inferencing. Conventional constant-processing AI inferencing requires relatively constant amounts of hardware (resources), so it is easy to accommodate the demands. In event-driven inferencing, on the other hand, the required hardware resources change depending on the event, and it is necessary to prepare resources that can cope with an increase in load due to a concentration of events, but it is undesirable to leave resources reserved for peak times idle during normal times.

Server-oriented techniques (e.g., Triton Inference Server [4], KServe [5]) can be used to dynamically allocate hardware resources to suit changing inference requirements, but such techniques are generally designed for specific on-demand use cases. At SIC, we are researching and developing inference-resource sharing, which is an extension of server-oriented techniques for real-time stream processing. By using inference-resource sharing, it becomes possible to share inferencing resources among streams and obtain statistical multiplexing benefits by bundling multiple streams with different peaks in real-time stream-processing use cases.

6. Future directions

In this article, we introduced the world view of a software-driven city (i.e., a smart city) achieved with a city-scale CPS, AI-inferencing infrastructure that can efficiently process high-resolution and multi-camera images, concept of event-driven inferencing, and its basic techniques of model cascading and inference-resource sharing.

By using model cascading and inference-resource sharing, and by introducing the concept of event-driven inferencing, we can expect to significantly reduce processing loads and energy consumption to practical levels, enabling the implementation of AI inferencing required by smart cities in the IOWN era. By accumulating the basic techniques for IOWN, we can also implement AI systems that can analyze and make decisions faster than humans. We will then create services that are safer, more accessible, more sustainable, and more comfortable for everyone and solve a variety of social issues.

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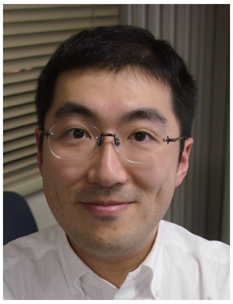

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Test-activity Analysis for Efficient Iterative Testing

Haruto Tanno, Hiroyuki Kirinuki, Takahiro Kawaguchi, Masaki Tajima, Morihide Oinuma, and Tatsuya Muramoto

Abstract

There is a growing demand for the early release of software while holding down costs. Software testing, which makes up a large portion of overall development costs and is essential to ensuring a certain level of quality in software, can be viewed as the cornerstone of quality, cost, and delivery in the development process. The NTT Software Innovation Center has developed technology that dramatically improves the efficiency of software testing and has made it available as open-source software. In this article, we introduce this technology.

Keywords: software testing, exploratory testing, test script

1. Importance of software testing

The software-development process is summarized in **Fig. 1**. In this process, software defects that could not be removed during testing are released in that state to the user, so testing is critical to software quality assurance. However, attempting to do all testing manually can be extremely costly. Users' needs have been changing rapidly, and software and hardware that constitute the operating environment have likewise been evolving at a rapid pace. This makes it necessary to revise software quickly as the need arises and release software updates frequently at short intervals. However, to conduct software releases frequently while maintaining a certain level of quality, testing cannot be limited to just the new additions. It is also necessary to conduct regression testing with respect to all existing features at every release to check whether they have been adversely affected by new features or the like, and this can also incur high costs. The NTT Software Innovation Center seeks to revolutionize testing—the cornerstone of quality, cost, and delivery in software development—and achieve a quantum leap in productivity in the software-development process.

2. Current state of software testing

The purpose of software testing includes checking that the software is behaving appropriately and reducing the number of software defects. The main tasks in the testing process are test design and test execution. Test design involves identifying test variations that should be carried out, exhaustively designing test

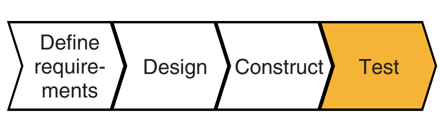

Fig. 1. Software-development process.

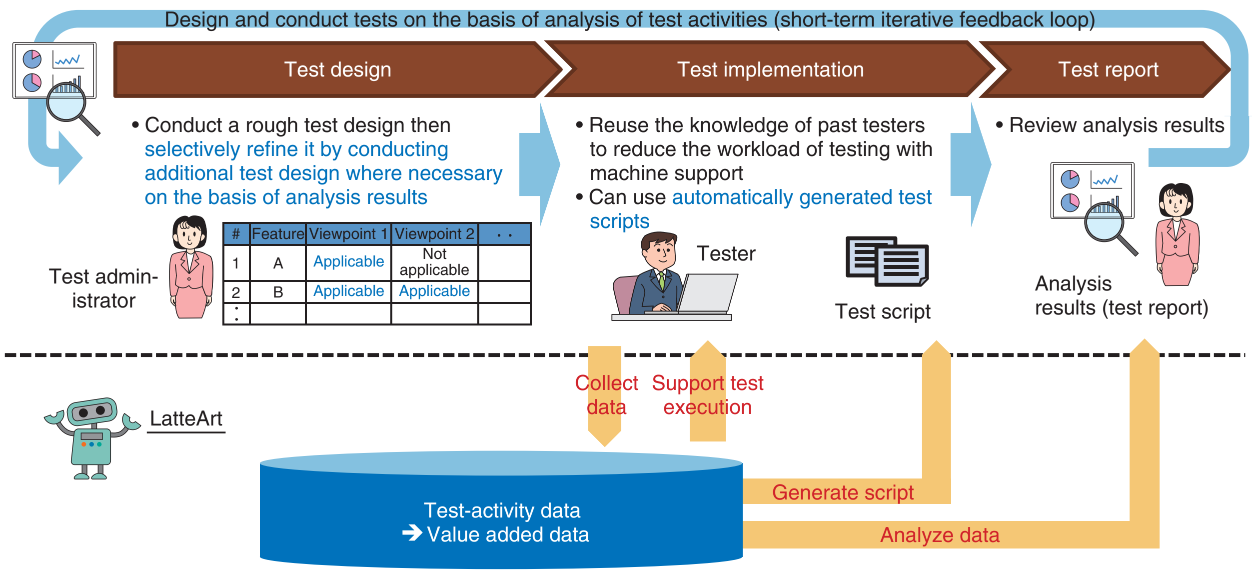

Fig. 2. The world we are aiming for.

cases, and for each test case, refining a specific procedure for executing the test and creating a script for automatic execution. Next, test execution involves providing input data for each test case, running the software, and checking whether the software is behaving as expected. We believe that there are three major issues with current tests.

The first issue is the high cost of designing exhaustive and detailed tests on the basis of conventional pre-planned index values. The pursuit of completeness to improve quality can take a massive amount of time. Moreover, to ensure that these tests are reproducible and auditable, a great deal of time and effort must be expended to create long-winded test-case tables containing intricate descriptions of the test procedures and other details of each test case.

The second issue is that executing tests requires skill and huge amounts of processing time. For each of the many test cases, it is necessary to follow the set procedure to manipulate and input information to the application under test then check the results. It takes much time to implement each test case in accordance with the correct procedure.

The third issue is the costs incurred in automating regression testing, which is required when issuing releases frequently in short cycles. Although many frameworks and libraries, such as JUnit and Selenium, are currently available for automatically executing tests, scripts must be created for such automatic execution, which can be very time consuming. To make it worse, a completed script does not mean that no more work is needed since it must be revised together with any revisions made to the software targeted for testing. This type of maintenance work is also labor intensive.

3. The world we aim for

To achieve ultra-high-speed development that can handle increasingly diverse and vague business requirements and rapidly evolving businesses, the approach taken by the NTT Software Innovation Center is to establish artificial intelligence (AI) development technology that can substitute or even excel in some human work and develop software through human-AI cooperation. To implement testing that facilitates ultra-high-speed development, we are aiming to achieve the world shown in **Fig. 2**.

In our approach, instead of haphazardly pursuing completeness, we select the locations that should be tested and concentrate our efforts there. In addition, we make successive judgments as to what locations to select and concentrate on by collecting and analyzing test-execution conditions and results. This approach solves the problems surrounding traditional exhaustive testing and achieves a quantum leap in testing efficiency. Since the collected data on the test-execution status and results includes detailed test procedures, it is possible to ensure that the test results are reproducible and auditable (addressing the first issue). Furthermore, by collecting test-activity data and using them to automatically generate easy-to-maintain test scripts, it becomes easier to automate regression testing, which enables prompt releases after making software updates (addressing the third issue).

Finally, once a large quantity of test-activity data has been accumulated, it will be possible to reuse the knowledge of previous testers. This knowledge will not only be of assistance in the automatic execution of procedures that are repeated during test execution but will also make it possible to provide test recommendations to improve test quality. Therefore, we aim to achieve dramatic labor savings in the execution of tests (addressing the second issue).

The NTT Group develops many business applications that use web applications as front ends and tests these applications through integration testing. In this article, we describe LatteArt, our technology for integration testing, which requires efficiency improvements, and how it addresses the first and third issues mentioned above.

4. LatteArt: Analyzing test-activity data for efficient iterative testing

A business application has many use-case scenarios, features, and screens, and each screen may have many combinations of input patterns. This incurs high costs in traditional exhaustive testing. While there are tools that support test design through automatic design of exhaustive testing based on the type of model (e.g., software-design model), they have the drawback of incurring additional costs for the creation of software-design models. In addition, automating the testing of web applications requires the creation of test scripts for executing screen operations automatically. Such test scripts can be created by means of, for example, capture & replay tools such as SeleniumIDE without requiring advanced skills, but creating scripts in this manner still requires work. Moreover, because test scripts recorded using capture & replay are not modularized, they are difficult to modify and have low maintainability.

To solve these problems, we developed a test-activity data-analysis technology called LatteArt that implements efficient iterative testing. LatteArt has the following features.

(1) **Test-activity data collection**: Automatically accumulates test-activity data consisting of the tester's web application logs and screenshots as well as information input by the tester while executing tests, including test objectives, discovered bugs, and other findings.

(2) **Analysis of test-activity data**: Analyzes test-activity data that have been collected automatically and allows them to be visualized with various data models [1, 2]. For example, these data can be visualized using the models shown in the sequence diagram and screen-transition diagram of **Figs. 3** and **4**, respectively. This feature makes it possible to check the sufficiency of tests from time to time and supplement the minimum necessary tests to ensure that testing is conducted effectively. In addition, based on these test-activity data, it automatically generates test-case tables and information equivalent to test results, eliminating the need for long-winded test-case tables containing intricate descriptions of the test procedures that have thus far been created.

(3) **Test-script generation for regression testing**: This feature automatically generates a modular and highly maintainable test-script template based on page object patterns from test-activity data [3]. It also automatically generates documentation [4] to accompany and improve the readability of test scripts when editing. This documentation also includes screen-transition diagrams to show what screen transitions the test will execute and screenshots that show the elements being manipulated. Examples are shown in **Figs. 5** and **6**. This makes it easy to implement and maintain test scripts and allows regression testing to be automated with little effort.

5. Achievements and future outlook

We are currently evaluating the application of LatteArt through joint experiments with NTT Group companies and are receiving positive responses from development sites. LatteArt has been well received in presentations at academic societies in Japan and has received a number of awards. Since short-term iterative testing using LatteArt is a new testing method, we believe it is important to create a platform with which this new testing method can be understood and widely accepted by stakeholders (developers and system owners) both inside and outside the NTT Group. To this end, we have launched a LatteArt open-source software (OSS) community and released its source code on GitHub [5].

Going forward, we will leverage the data obtained

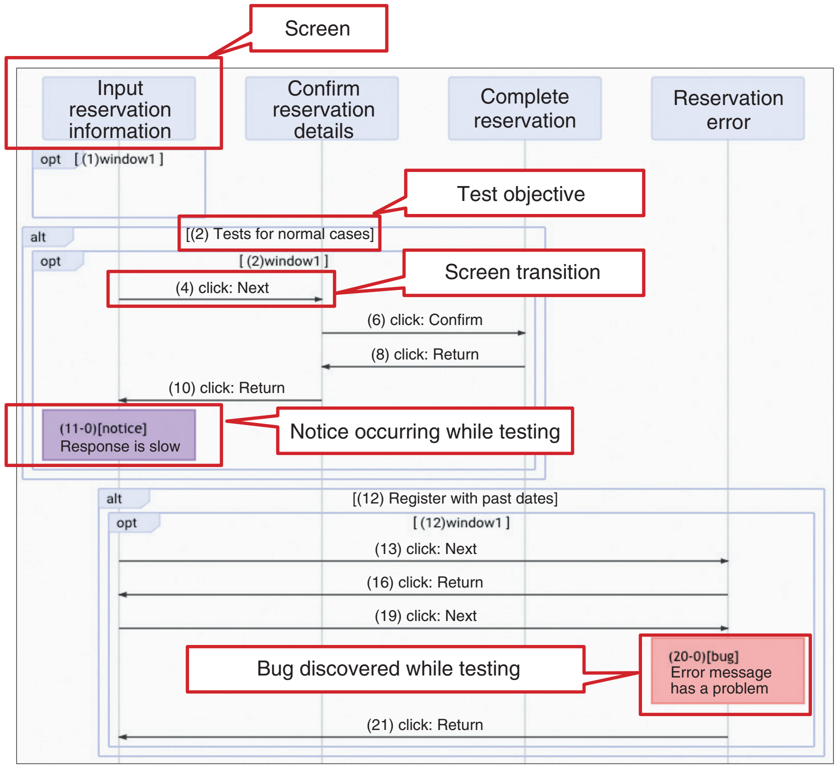

Fig. 3. Sequence diagram.

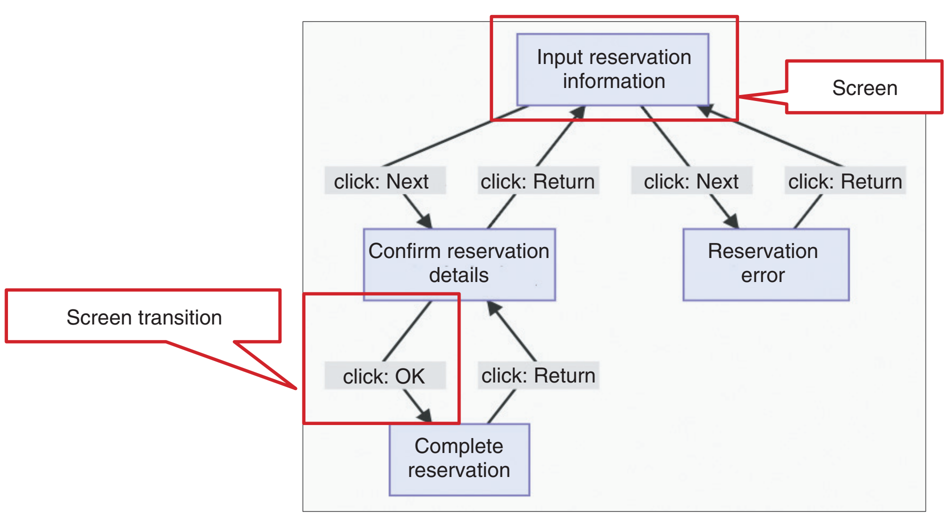

Fig. 4. Screen-transition diagram.

in practice to extract the knowledge of past testers from the large amount of accumulated test-activity data. By doing so, we aim to provide test recommendations and automate the preliminary groundwork that is repeatedly executed during testing, making testing much less labor-intensive and further improving its overall efficiency. In addition, we intend to develop a test-innovation ecosystem centered on the

```
doGotoNext({
  reserveMonth,
  // · · · · ·
}) {
  this.reserveMonth.setValue(reserveMonth);
  this.reserveDay.setValue(reserveDay);
  // · · · · ·
  return new ReservationDetailsConfirmation( );
}
```

Fig. 5. Test script.

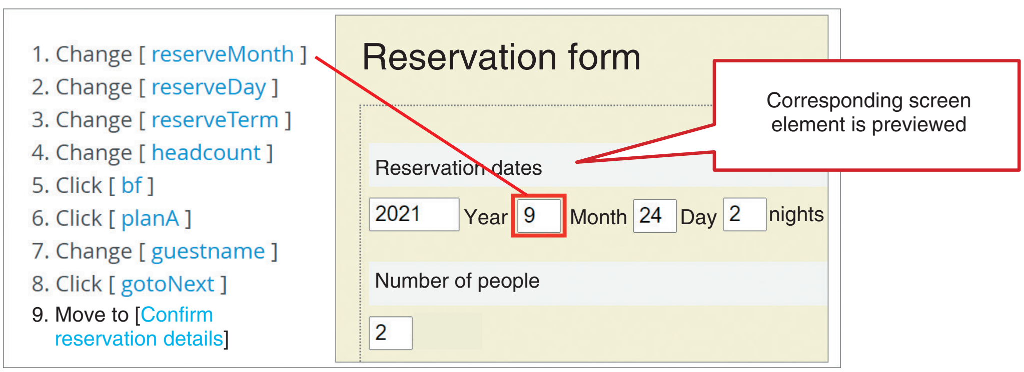

Fig. 6. Test-script documentation.

LatteArt OSS community through collaborations not only within the NTT Group but also with external organizations such as companies and universities to provide access to diverse knowledge from industry and academia. To achieve the world we are aiming for, we hope to continue making steady advances in our research and development one step at a time.

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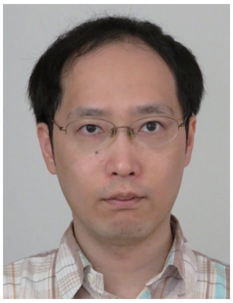

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Nanomechanics: Outline and Future Prospects

Hiroshi Yamaguchi and Hideki Gotoh

Abstract

Microelectromechanical systems (MEMS) technology, which uses the mechanical motion of miniaturized structures artificially fabricated on a chip, has been used in various fields such as mobile communications and Internet-of-Things devices. This article introduces the concepts and future prospects of nanomechanics technology, which further extends the functionalities from MEMS technology, focusing on research activities conducted at NTT laboratories.

Keywords: nanomechanics, phonon, nanotechnology

1. What is nanomechanics technology?

What do you imagine when you hear the word "nanomechanics"? The term "nanotechnology" has been used for a long time, so I think many people know that "nano" refers to a very small object. The origin of this word is the unit "nanometer (nm)," which represents an extremely small size of one billionth of a meter. Such minuteness is not easy to imagine, but, to put it into perspective, atoms range in size from only about 0.1 to 0.2 nm. The next unit is "micrometer (μm)," which is one millionth of a meter, and nanotechnology deals with sizes ranging from about 1 nm to 1 μm. Incidentally, the novel coronavirus that has caused the COVID-19 pandemic is about 100 nm, so it falls within the size range of this technology.

What does "mechanics" mean? The first thing that comes to mind when we hear "mechanics" is possibly Newtonian mechanics, which led to the discovery of gravitational force through the observation of a falling apple. It describes the relationship between the motion of an object (apple) and the force applied to it. Therefore, nanomechanics is a field of study focused on the relation between the force applied to objects and their motion in the extremely small world represented by the size of viruses. The nanomechanics we are studying is an attempt to develop technology that uses the physical laws governing such small force and motion.

Forgetting about the microscopic world for a moment, imagine a temple bell. The bell makes a sound because the metal that makes up the bell causes periodic elastic vibrations. This behavior can also be accurately described using the laws of physics. If the vibration is repeated 440 times per second, the sound has the frequency of 440 hertz (Hz). This corresponds to the reference pitch "la" in the C-major scale used in music. The frequency of 523.23 Hz produces a slightly higher "do" sound, and 783.98 Hz produces a higher "so" sound. The faster the vibration, the higher the sound frequency, so it is easy to imagine that the smaller the bell is, the higher the frequency will be. Therefore, a nanometer-sized bell will vibrate at a very high frequency. This is the essence of our research; namely, we are using cutting-edge microfabrication technology to create extremely small "bells" and developing a technology that uses their high-frequency vibrations.

2. Nanomechanical oscillator

Of course, making a submicrometer-scale structure with the shape of a temple bell is not straightforward with present microfabrication technology. We therefore use simpler structures that are easier to make. **Figure 1** shows typical examples, where Fig. 1(a) is a structure called a cantilever. It is just like a diving

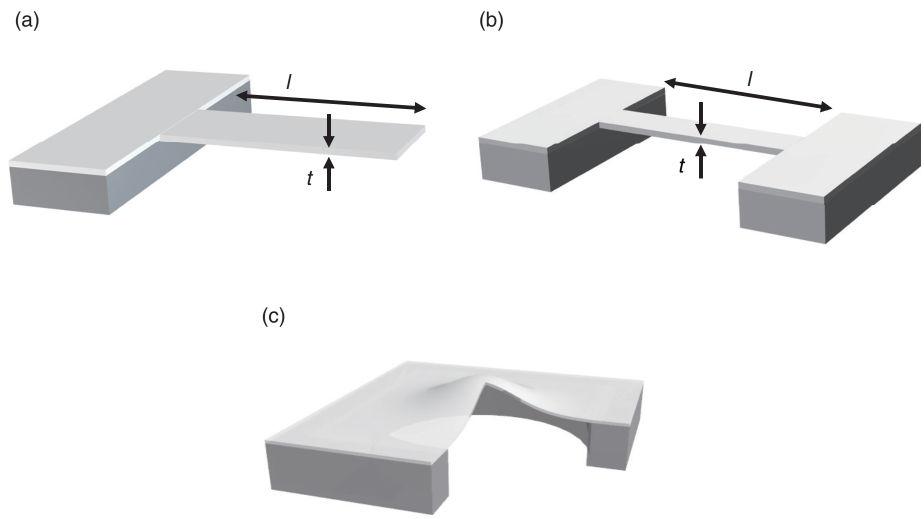


Fig. 1. Examples of nanomechanical structures: (a) cantilever; (b) doubly clamped beam; and (c) circular membrane structure.

Table 1. Vibration frequencies of cantilever and doubly clamped beam. These values are calculated for GaAs with the length-to-thickness ratio (l/t in Fig. 1) of 20.

Beam length (l)	1 mm	100 μm	10 μm	1 μm	100 nm
Cantilever	32 kHz	320 kHz	3.2 MHz	32 MHz	320 MHz
Doubly clamped beam	200 kHz	2 MHz	20 MHz	200 MHz	2 GHz

board at a swimming pool, and it vibrates when you hit the edge. The structure in Fig. 1(b) is called a doubly clamped beam, and it is shaped like a bridge. Both ends of the beam are supported, so setting into vibration is harder than it is for a cantilever, and it has a higher vibration frequency. Both structures are thin and plate-like in shape, but their cross sections can have other shapes. The nanomechanical oscillator reported in the Feature Articles in this issue has a cylindrical or hexagonal cross-sectional shape of several hundred nanometers in diameter, which is produced by crystal growth. Figure 1(c) is a circular membrane oscillator, which acoustically vibrates like a drum. In this issue, we also describe a nanomechanical device called a phononic crystal waveguide, which guides and transmits elastic vibrations to form an acoustic circuit. In this waveguide, a number of membrane oscillators are connected with equal spacing.

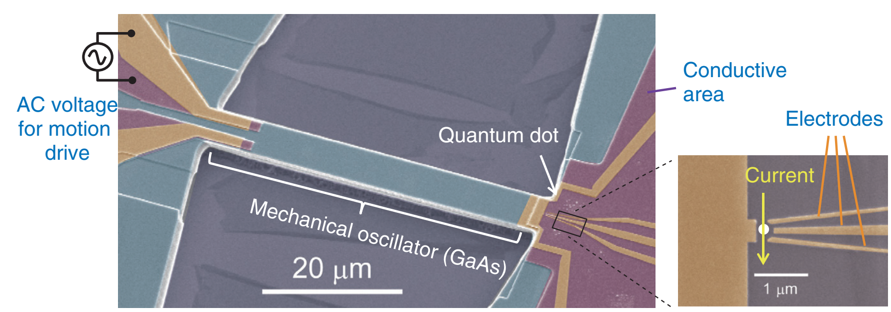
Table 1 shows how the frequencies of the cantilever and doubly clamped beam change with the structure size calculated for a typical semiconductor, gallium arsenide (GaAs). Even with the same shape, the doubly clamped beam has about a six times higher frequency than the cantilever. When its length is 100 nm, the frequency enters the gigahertz range. Gigahertz (GHz) is the frequency of the radio waves used for mobile phones, and it is 100,000 times higher than that of highest sound we can hear, which is about 10 kilohertz (kHz). Therefore, by using nanomechanical structures, it will be possible to develop a technology that can control acoustic vibrations at extremely high frequencies, called ultrasonic waves or extreme ultrasonic waves. Focusing on this unique feature of nanomechanical oscillators, we have been researching nanomechanics for nearly 20 years. The frequencies we are studying cover the range from around 100 kHz to 1 GHz, but, in this issue, we mainly introduce our research activities in the relatively low frequency range of up to 10 megahertz (MHz).

3. Applications of nanomechanics

Microelectromechanical systems (MEMS) are

Table 2. Comparison of electronics and micro/nanomechanical devices. In micro/nanomechanics, nonlinear devices and quantum devices are still subjects for future research, and their development is expected to lead to a large technological breakthrough similar to diodes and transistors.

	Linear devices	Nonlinear devices		Quantum devices
		2-terminal	3-terminal	
Electronics	Inductors Capacitors Resisters	Diodes	Transistors	Quantum bits Quantum memory
	Resonators Filters	Demodulators Rectifiers	Amplifiers Logic Memories	Quantum computation Quantum sensing
Micro/nanomechanics	Resonators	Targets in our studies		
	Radio-frequency filters Sensors Microphones			



AC: alternating current

Fig. 2. Electron microscope image of a mechanical oscillator integrating a quantum dot. The vibration of the beam structure applies a periodic strain to the quantum dot. Since this strain induces a large change in the current flowing through the quantum dot, the vibration of the beam structure can be detected with high sensitivity by measuring the current.

being widely and actively studied for using such elastic motion of an artificial structure. Our research uses two unique approaches to extend the device functionalities in MEMS technology. The first is to use the nonlinearity of the elastic properties. "Nonlinearity" may be an unfamiliar word, but consider that common semiconductor devices such as diodes and transistors have demonstrated a variety of functions due to nonlinearities. These functions cannot be found in devices with only linear characteristics such as inductors, capacitors, and resistors. By harnessing nonlinear characteristics, we aim to create mechanical devices with innovative functions similar to those of diodes and transistors. The other approach is to create new functions by combining functional materials such as semiconductors and optical materials. Such materials, which have thus far been used in electronic and optical devices, can also be applied to mechanical devices to create new principles by combining the optoelectronic function with elastic vibration. By incorporating nanostructures known as quantum nanostructures, it is possible to apply such mechanical devices to quantum technologies, which are attracting much attention (**Table 2**).

Figure 2 shows an electron micrograph image of a quantum-sensor device as an example of quantum nanomechanical technologies. A quantum dot is embedded at one of the two clamping areas of the beam structure, making it possible to detect elastic vibration with ultrahigh sensitivity. Vibrations of 0.1 picometers (ten trillionths of a meter), corresponding to the diameter of an atomic nucleus, can be detected through current measurement. This electromechanical device makes it possible to detect displacement caused by extremely small forces applied to the beam, thus to use it as an ultrasensitive acceleration, magnetism, molecular, and atom sensors.

In the Feature Articles in this issue, we introduce five topics on which our group has made significant progress. First, as an example of nonlinear nanomechanics, we introduce a new method for generating chaos [1]. Chaos used to be regarded as random and uncontrollable behavior, which was considered an obstacle to its application. However, in the field of machine learning, this chaotic behavior is expected to play an important role in improving learning efficiency. Secure communications using chaos has also been proposed, so how to accurately control the chaos generation is now an important research subject.

As the second topic, we introduce phonon waveguides using phononic crystals [2]. The term "phonon" is used in a sense similar to "photon" for light or "electron" for electric current. A phonon is a sound particle that is the basic unit of elastic vibration. We developed a method of controlling the flow of phonons using nonlinearity. This research demonstrated a phonon transistor for the first time, which controls the propagation of sound waves in a way similar to how a transistor controls the electron flow in circuits. This device is expected to play a central role in phononic integrated circuits, where a large number of nanomechanical devices exchange acoustic signals.

The third topic is a new optomechanical device using a rare-earth element, which is a functional material widely used in fiber optics [3]. Optomechanics is a technology that combines the functions of both light and mechanics, and is one of the technological fields in which research has been making great progress. Rare-earth elements, such as erbium, are materials that absorb and emit light in the telecom wavelength bands and can be widely used in optical communications and quantum technologies. In this issue, we report on a new method of mechanically controlling light emission from erbium atoms by incorporating them into a cantilever.

The fourth topic covers the detection of the mechanical vibration of a semiconductor nanowire with high sensitivity by using a unique optomechanical setup [4]. Semiconductor nanowires are self-organized nanostructures produced by crystal growth. Since no microfabrication method such as lithography is used for forming their three-dimensional shapes, the structures have high crystalline quality. In addition, it is possible to incorporate heterostructures, which are used in semiconductor lasers, high-speed transistors, and various quantum structures—the key elements in optoelectronic and quantum technologies. By using nanowires as nanomechanical structures, it is expected that advanced functions achieved by combining electronic, optical, and quantum devices will be incorporated into mechanical devices.

The final topic is a novel fabrication method in which an inkjet-printing technique is used to fabricate nanowire mechanical devices [5]. Inkjet printing is a basic technology used in our daily lives, but we have recently seen it used as a new microfabrication technology. This section describes how inkjet printing can be used to arrange semiconductor nanowires at desired positions on a semiconductor wafer and assemble them as nanomechanical devices.

4. Future prospects

Compared with electronic and optical devices, nanomechanical devices are still in the early stages of research, and there is a possibility of significant developments in the future. NTT laboratories are conducting research to develop new information processing technologies such as machine learning, Internet of Things, and quantum technologies, where the nanomechanical devices introduced in this issue are expected to play essential roles.

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New Method of Chaos Generation by Using Nanomechanical Oscillator

Samer Houri, Motoki Asano, and Hiroshi Yamaguchi

Abstract

Chaos is a naturally observed phenomenon characterized by its irregular and complicated behavior. Although chaos has been long recognized as a topic of academic importance, its implementation in modern technological products and devices remains wanting. However, with advances in security and artificial-intelligence technologies, attempts to use chaotic signals have begun to materialize. In this article, we report on a new simple and versatile chaos-generation method using a nanomechanical oscillator developed by NTT laboratories.

Keywords: chaos, nanomechanics, libration

1. What is chaos?

If you look up the word "chaos" on the Internet, you are likely to find loose definitions, such as "an expression describing a chaotic situation or aspects in which various elements are jumbled and incoherent." Chaos conjures up images of unpredictable irregularities, such as "the stock prices are chaotic right now," or "my desk is chaotic." In mathematics, however, chaos is a well and rigorously defined subject of study. If one wants a definition, although not mathematically exact, one can say "chaos is a seemingly disordered complex movement that evolves according to well set laws." For physicists and engineers, chaos has attracted attention for its behavior that lies between irregular random motion and periodic regular motion [1].

For a researcher, chaos has several attributes. First, it has reproducibility, meaning that under the same initial conditions a chaotic system will repeatedly show the same behavior. Thus once the initial state is perfectly known, it is, in principle, completely predictable. This is an important property that distinguishes it from random motion. However, chaos is characterized by the *butterfly effect*, in which the tiniest difference in the initial conditions will cause a large change, which practically makes chaos all but unpredictable. In principle, if the initial state is completely known, one can accurately predict the future evolution of the system; however, even the slightest mistake or difference in the initial state—say 0.001%—will make a large difference in how the system behaves after a while.

Perhaps a good example would be to imagine the bouncing of a rugby ball. It would not surprise you to know that the motion of a rugby ball follows the laws of physics, the same laws that describe bowling balls and airplanes, and according to those laws, if the initial conditions can be reproduced (speed, angle, twist…), then the motion of the rugby ball can also be reproduced. However, anyone who enjoys watching a rugby match understands how difficult that is, and how only slight changes in angle or speed would quickly lead to a different trajectory and a loss for your favorite rugby team.

Another characteristic of chaos is that such seemingly complex behavior can occur in mathematically simple dynamical systems. To be clear, chaos does occur in large systems with many components (degrees of freedom as the mathematicians call them). Think of, for example, the turbulent waters of a flowing river or the behavior of weather that depends on many parameters, e.g., humidity, wind speed, cloud cover, precipitation, temperature, and pressure. However, the appeal of chaos is that it equally appears in simpler systems. For instance, it has long been known that three stars orbiting each other could lead them to have chaotic orbits, even if we neglect the influence of every other object in the universe upon these three stars. That such simple systems can generate such a complex behavior is certainly a property that engineers, physicists, and mathematicians find particularly interesting.

Despite this interest in chaos as a scientific phenomenon, it has remained rather untamed and difficult to apply technology. Nevertheless, serious efforts are underway to put the properties of chaos to applied use, such as secure communication, where chaos' complex signals are used to encrypt and mask information, or the use of chaos in efficient machine learning that uses a state known as the *edge of chaos*[*1] to execute such computation efficiently.

Some of the questions of practical interest, if chaos is to serve in applications, are what are the necessary conditions to reliably generate chaos?, Can such reliable chaos be generated using low-power methods?, and What exactly are the properties of the generated chaos? Motivated by this background of challenges, we developed and demonstrated a chaos-generation method that can successfully generate chaos in a reliable fashion all while using low power in a microelectromechanical device. The following sections describe this method.

2. Chaos generation via libration motion

Microelectromechanical systems (MEMS), as their name suggests, are miniaturized devices that can either produce or detect mechanical forces. Other than their size, MEMS devices are distinct from conventional electromechanical systems (think electric motors or even sound speakers) in that they are fabricated using the same materials and processes that are used to make the electronic devices and integrated circuits that power our cellphones, computers, and cars. Therefore, MEMS devices have been extremely successful as various sensors, high-frequency filters, accelerometers, gyroscopes, and portable digital projectors.

It is therefore not surprising that efforts to generate chaos using MEMS or further-miniaturized nanoelectromechanical systems (NEMS) mechanical oscillators[*2] have attracted significant attention. Such efforts are motivated by the availability of low-cost MEMS/NEMS devices on the one hand, and on the other the possibility to directly integrate them with electronics in packages that combine both sensors, signal processors, and machine learning.

Despite multiple successful demonstrations of chaos generation using MEMS oscillators, they remained more in the realm of fundamental research rather than application. One of the main reasons is the need for complex device geometries such as comb-shaped electrodes. Another especially impactful reason is the need to apply high voltages on the order of several tens of volts, which may not seem very large by comparison to the electric wall plug but considered quite substantial by microelectronics standard. Researchers working at NTT laboratories have demonstrated a simple and low-power, i.e., low voltage, method for the generation of chaos in MEMS/NEMS devices by simply applying two slightly different frequencies to the mechanical device. This method leverages a type of motion known as *libration*[*3] to induce chaos with drive voltages on the order of a fraction of a volt [2].

Figure 1 shows the difference in the transition to chaos generated using a MEMS/NEMS oscillator between the classical method and above method developed by NTT laboratories. First, consider the classical method, with which the oscillatory is forced

*1 Machine learning and edge of chaos: Machine learning is one of the building blocks of artificial intelligence. This technology enables a computer to find common patterns and rules from large-scale data and apply them to new input data to make various judgments and predict the results. There are several methods for machine learning, however, unlike deep learning, which adapts to the network, with reservoir computing, only the output layer is modified while the network remains unchanged. In reservoir computing, it is often pointed out that using *the edge of chaos* state improves performance.

*2 Mechanical oscillator: An artificial structure in which mechanical vibration can be produced. Examples include acoustic musical instruments, such as violins and harps, where the musical note is generated thanks to the motion of a structure (cord or bell cup). With the developments in the semiconductor industry, it is now possible to produce mechanical oscillators smaller than a hair's width on a semiconductor chip, which are MEMS. One of the most commonly used shapes for mechanical oscillators is the doubly clamped beam used in this study.

*3 Libration: Libration is used to (usually) indicate a small-amplitude periodic motion on top of another large-amplitude (and usually higher frequency) periodic motion. For instance, astronomical objects, such as the moon and Earth, have regular periodic motions of rotation and revolution, but they also have other slow periodic motions. The latter are librations and small compared with the rotation and revolution and have periods on the order of several years to tens of thousands of years. The libration motion is caused by a variety of factors, including the ebb and flow of tides and the gravitational pull of the other planets. This is equally the case of mechanical oscillators under the effect of two narrowly separated frequencies where the overall influence is to have a periodic motion plus a weak low-frequency libration envelope (AM envelope). If this libration motion is in resonance with nonlinear properties of the device, then chaos may be generated more easily.

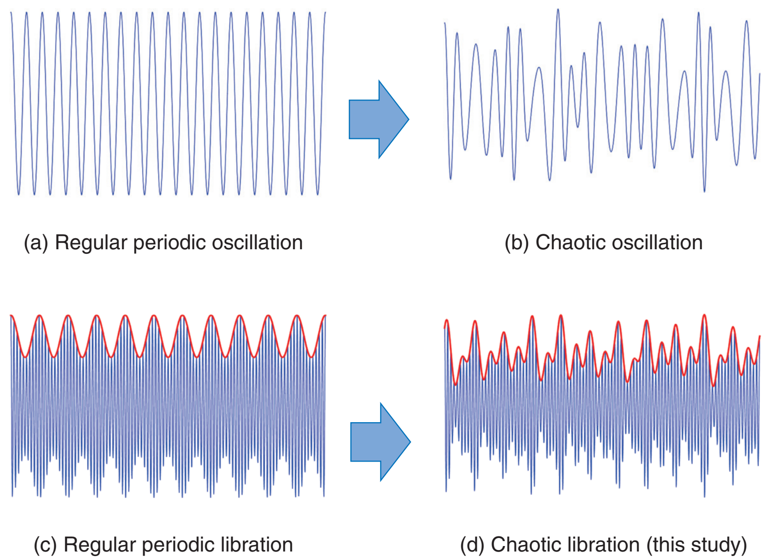

Fig. 1. Schematic diagram of chaotic vibration. The horizontal axis represents time, and the vertical axis represents the displacement of the vibrator. (a) Regular periodic motion of a normal oscillator. (b) Periodic motion in a chaotic state. The amplitude and phase of the vibration are irregular. (c) Regular libration. The amplitude (red line) of the fine vibration indicated with the blue line changes periodically. (d) Chaotic libration. The change in vibration amplitude shown with the red line indicates irregular behavior.

from a regular periodic motion (Fig. 1(a)) into producing a chaotic motion (Fig. 1(b)). To achieve such a transition, it is necessary to have a large structure, known as a comb-shaped electrode, and apply a high voltage to find the right conditions to transform the periodic motion into chaotic oscillations.

With the new method, chaos generation is facilitated by the use of libration motion, where the periodic motion is composed of two frequencies not just one (Fig. 1(c)), and the first periodic motion is modified periodically by the second periodic motion. This is not unlike amplitude modulation (AM) found in AM radio. The team of NTT researchers realized that it is possible to leverage this motion in a nonlinear nanomechanical oscillator to create a chaotic motion without the high voltage and special design constraints found with the classical method (Fig. 1(d)). The researchers were equally able to successfully identify the necessary conditions for the generation of chaotic motion.

Figure 2 shows a diagram of the experimental equipment used in this study. The beam structure is made from layers of piezoelectric semiconducting materials known as gallium arsenide (GaAs) and aluminum gallium arsenide (AlGaAs). By applying an alternating current (AC) voltage to the electrodes shown in the figure, the beam starts to oscillate in the direction shown with the red arrow. The vibration of the beam is measured using a laser interferometer device, and the amplitude of vibration is split into a sine and cosine components using a lock-in amplifier (note that these are the same sine and cosine components that telecommunication engineers are so familiar with).

The method for generating the libration motion and chaos is quite simple. Apply two different AC frequencies (f_1 and f_2 in the figure) to drive the mechanical device, if the frequencies are not very different, then they will cause a *beat* that is equal to their difference. This beat is what causes the AM shown in Fig. 1(c).

Another way to visualize this AM is to draw the sine and cosine components, as done in **Fig. 3** (right column; (d), (e), (f)). By applying the two AC frequencies, the AM envelope, shown in Fig. 3 (left column; (a), (b), (c)), is periodic at first (Fig. 3(a)). This periodicity is seen as a simple closed orbit (also called libration orbit, hence libration motion) if observed in the sine and cosine plots (Fig. 3(d)). By slightly changing the drive voltages, the AM envelope undergoes what is called a period-doubling bifurcation, and we see clearly that there is a new second period even though we have not changed the frequencies of the two drive tones (Figs. 3(b) and (e)). This

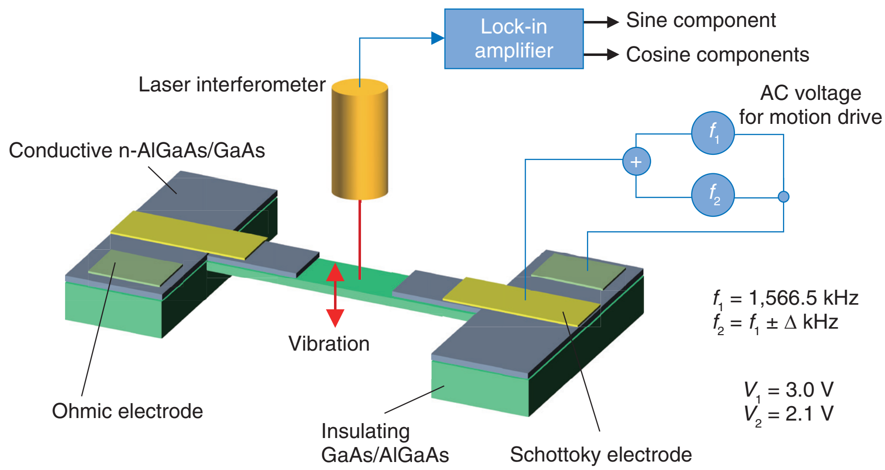

Fig. 2. Schematic diagram of the mechanical oscillator and measurement setup used in the experiment. The beam structure is 150 µm long, 20 µm wide, and 0.6 µm thick. Electrodes, which can electrically drive and detect vibrations, are formed on the surface of the structure. By applying AC voltages including two frequencies to these electrodes, chaotic vibrations are generated. The vibration is detected using a laser interferometer, and the sine and cosine components of the vibration are individually measured using a lock-in amplifier to confirm the chaos. The vibration frequency of the beam is approximately 1.6 MHz.

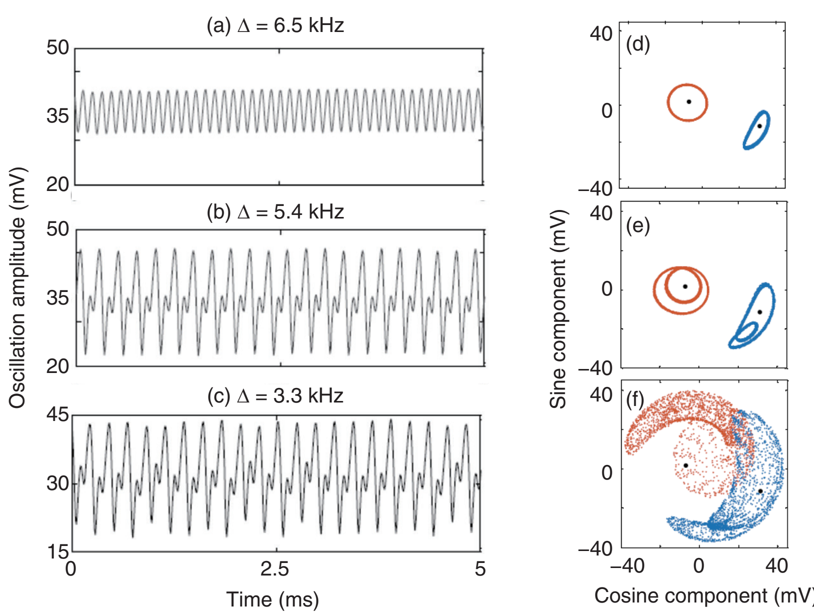

Fig. 3. (a) - (c) Time variation of measured vibration amplitude (cosine component). They correspond to the red curves shown in Fig. 1. (d) - (f) Trajectories of the sine and cosine components of the vibration amplitude. Δ represents the frequency difference between the two AC voltages. At Δ = 6.5 kHz, the amplitude changes periodically, and the trajectories of the sine and cosine amplitudes are closed curves. However, when Δ reaches 5.4 kHz, the periodicity of the oscillation starts to change, and when Δ reaches 3.3 kHz, it shows chaotic and irregular amplitude change; the trajectories in (f) are not lines but are distributed over a wide area.

period-doubling bifurcation is a sign that we are well on our way to chaos, and by changing the drive forcing just a little bit more, the AM envelope and libration motion both demonstrate a breakdown of the main periodic motion and onset of a chaotic motion (Figs. 3(c) and (f)).

To rigorously demonstrate that we have achieved a chaotic motion, we need to calculate the Lyapunov exponent[*4] which quantitatively confirms the property of chaos to produce large changes due to small differences in initial conditions. In our collaboration with Tokyo Institute of Technology, we confirmed that such a property is indeed present using numerical calculations and simulations.

This new chaos-generation method has three major advantages. First, it is possible to use small voltages (~1 V in the experiment), which makes it easy to interface with current low-power electronic circuits. Second, because large structures (by MEMS standards), such as comb-shaped electrodes, are not required, the process of miniaturization and integration is more convenient. The third advantage is that this method is not limited to mechanical oscillators but can be implemented in a variety of devices including optical resonators used in laser technology, therefore combining the roles of optical communications and secure encryption in a single system.

3. Future outlook

In this article, we presented a new chaos-generation method using libration motion in a nanomechanical oscillator was presented. This method can generate chaos in nanomechanical devices with a drive voltage that is more than an order of magnitude smaller than with the classical method, all while being more suitable for miniaturization and integration. The tradeoff being, that since, as shown in Fig. 1, the frequency of the generated chaos is smaller than that of the original vibrations, a higher frequency oscillator is needed to generate a chaotic signal with a practical bandwidth. We succeeded in demonstrating nanomechanical oscillators with frequencies up to the GHz using phononic crystals. We will continue to work on improving the performance of such systems and hope to enable applications such as machine learning using integrated nanomechanical devices.

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*4 Lyapunov exponent: In a chaotic dynamical system, the coordinate representing the dynamical system (for example the speed of the oscillator) varies unpredictably with time. It takes only a slight inaccuracy in the velocity measurement to make the system unpredictable. As a mathematical indicator, the Lyapunov exponent indicates how the distance between the predicted and actual motion increases exponentially with time. For a system to be chaotic, the Lyapunov exponent needs to be positive.

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Control of Elastic Waves Using Phonon Waveguides and Phononic Crystals

Daiki Hatanaka, Megumi Kurosu, and Hiroshi Yamaguchi

Abstract

Sounds and heat are elementary excitations of lattice vibrations called phonons. In contrast to the widespread use of electrons and photons in signal processing devices and communications systems, the use of phonons as information carriers has been extremely limited because a technique to control them has not been developed. This article describes our research on a new platform called *electromechanical phononic crystal* for improving the on-chip control of phonons.

Keywords: phonon, phononic crystal, MEMS

1. Potential of phonons as information carriers

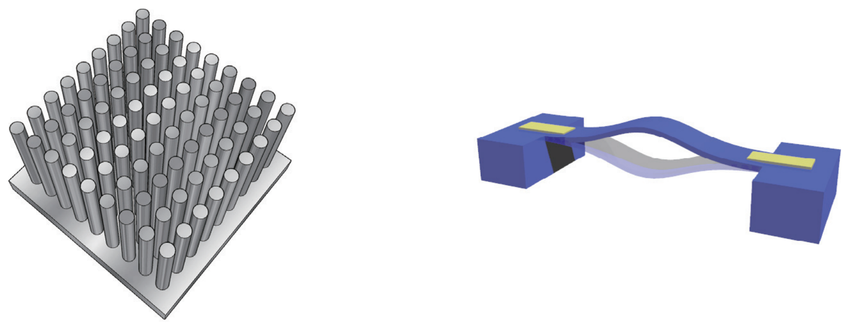
Phonons are the elementary excitations of atoms and lattice vibrations. Sound waves with a frequency ranging from 10^4 to 10^{11} Hz are called ultrasonic waves and have long been used as a signal source for echo sounding and sonar [1]. In information-processing systems, phonons, including ultrasonic waves, are byproducts generated during device operation and have been regarded as obstacles that disturb normal operation. Therefore, they have thus far not been used as information carriers.

Photons (light), which are attracting attention as the next-generation of information carriers, were originally used only in observations with instruments such as microscopes and telescopes. Later, the advent of new platforms, such as planar lightwave circuits and photonic crystals, improved the photon-control technology on the chip scale, thus led to the discovery of their present industrial value. Phonons also have a wave with dynamics compatible with photons. However, the wavelength of phonons is five orders of magnitude shorter than that of photons at a given frequency, and there is no radiation to free space and less energy loss. These physical properties are useful for satisfying the demand for further device miniaturization and energy-saving in high-frequency information-processing systems for the future Internet of Things society [1]. With that motivation, we are working to develop a platform enabling a variety of on-chip phononic operations.

2. Phononic crystals and microelectromechanical systems

Phononic crystals and microelectromechanical systems (MEMS) have long been known as phononic platforms. The former are artificial acoustic structures consisting of periodic structures of different elastic media and are the phononic analogue of photonic crystals (**Fig. 1(a)**) [1]. When a lattice constant (a) has a scale of the phonon wavelength (λ), the phonon-dispersion relation*1 is modulated by the periodic potential produced by the elastic structure.

*1 Dispersion relation (curve): The relationship between wave number and frequency. The wave number is the inverse of the wavelength and proportional to momentum. From this relationship, the wave number corresponding to the frequency is determined, and fundamental wave-propagation characteristics, such as propagation speed, are determined.



(a) Phononic crystal consisting of periodic array of metallic pillars

(b) MEMS composed of a mechanical beam suspended by a substrate

Fig. 1. Schematics of a phononic crystal and MEMS.

For example, a band gap*2 emerges in frequencies that satisfy the Bragg condition ($n\lambda = 2a$, n is a natural number), in which the phonon propagation with λ is prohibited. Furthermore, the formation of the band gap changes the dispersion curve, and the group velocity, which is determined by that slope, is also modified. Namely, phononic crystals enable us to spatially control the phonon propagation through their periodic structures. Therefore, in the field of acoustic engineering, artificial acoustic structures have been used as the basic structure for acoustic-wave control such as sound insulation.

MEMS have been intensively studied, mainly in the field of electronics for semiconductor engineering. They consist of a three-dimensional mechanical structure with nanometer and micrometer scales, such as a cantilever and beam, and can sustain ultrasonic vibration electrically excited on-chip (**Fig. 1(b)**) [2]. The acoustic impedance difference between the beam and support substrate suppresses the dissipation of elastic vibrations to the substrate, thereby sustaining resonant vibrations with a long duration (high quality factor, Q*3). Basic research on the nonlinear dynamics of MEMS has attracted much attention because the nonlinear response remarkably appears, which enables the vibration to be actively modulated via external stimulation. A variety of dynamic phonon controls, such as parametric effects*4 and frequency conversion through four-wave mixing*5, have been demonstrated in nonlinear mechanical systems. Thus, MEMS have the ability to dynamically control the phonon amplitude, i.e. the magnitude of elastic vibration, whereas they are incapable of spatial control due to them being localized structures. In contrast, phononic crystals have the ability to spatially control phonon propagation, although they are unable to dynamically control the phonon amplitude.

Note that the functions of these two platforms have a complementary relationship. We focused on this point and proposed a phononic platform called *electromechanical phononic crystal* created by the fusion of these different structures [3, 4]. This alternative system enables on-chip excitation, spatial transmission, and dynamic control of phonons simultaneously.

3. Electromechanical phononic crystal

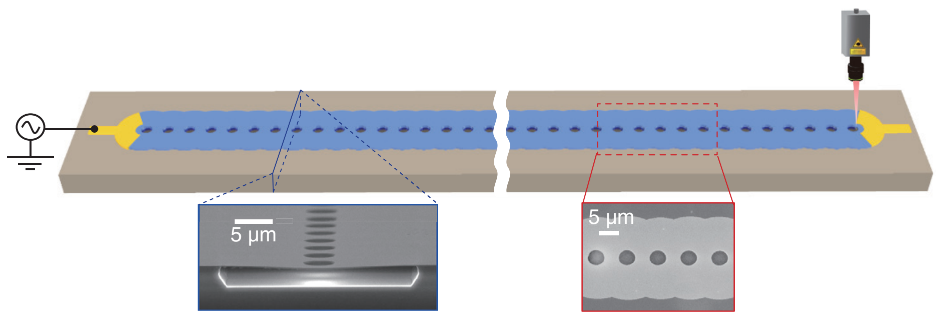
Electromechanical phononic crystal is composed of a waveguide structure in which 100 circular membranes with a diameter of 22 µm, made of gallium arsenide (GaAs), are periodically connected at the period of a = 8 µm, as shown in **Fig. 2(a)** [4]. The

*2 Band gap: A frequency band in which no dispersion relation of waves is given. This occurs when the wavelength (λ) and lattice constant (a) of a medium satisfy a specific condition (Bragg condition). In this case, propagating waves exhibit strong reflection from the periodic structure, and the transmission is strongly suppressed.

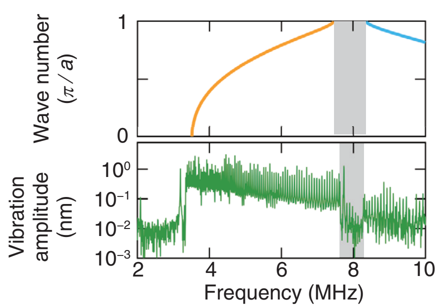
*3 Q factor: A dimensionless figure of merit ($Q = f_{res}/\Delta f_{res}$), used to evaluate the quality and vibration lifetime expressed by the ratio of the resonance frequency (f_{res}) to the full width at half maximum (Δf_{res}, the inverse of the relaxation time).

*4 Parametric effect: A phenomenon in which waves with different frequencies are mixed and a new wave with a frequency component of their sum or difference is generated. In the case of MEMS, this is achieved by periodically modulating the tension with an external signal.

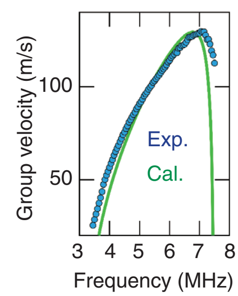
*5 Four-wave mixing: A method of frequency conversion of waves through third-order nonlinear effects. When two waves with different frequencies f_1 and f_2 are injected simultaneously, new frequency waves (f_3, f_4) emerge through this process. The values of f_3 and f_4 are determined to satisfy the energy conservation law ($f_1 + f_2 = f_3 + f_4$).



(a) Schematic of an electromechanical phononic crystal



(b) Dispersion relation of phonons (top) and frequency response of the device (bottom)



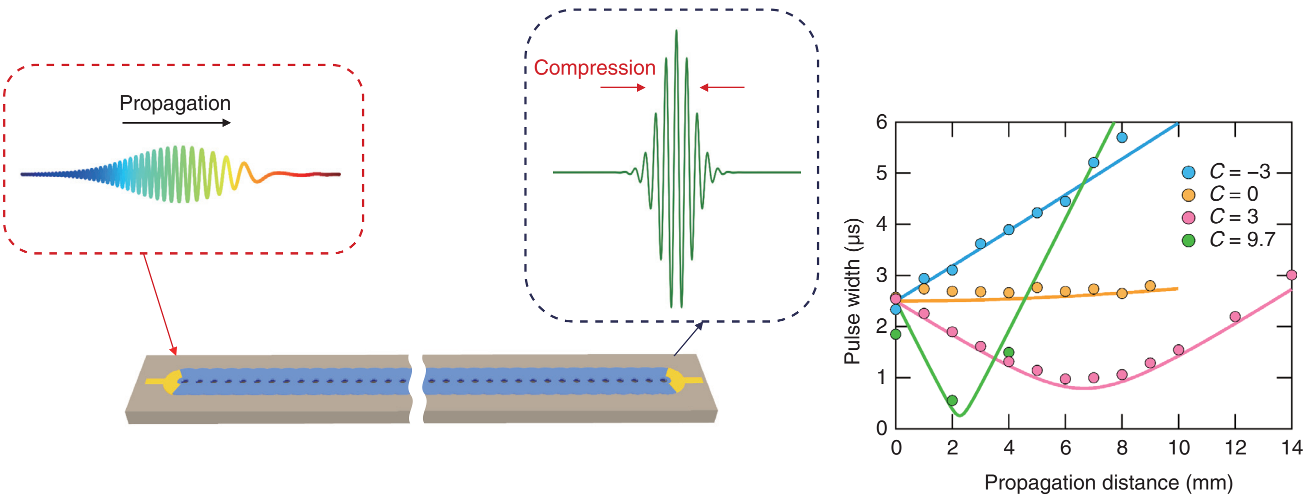
(c) Frequency response of measured and calculated group velocity as shown with blue and green plots, respectively

Fig. 2. Electromechanical phononic crystal and phonon transmission characteristics.

membranes are suspended from a GaAs substrate and vibrate like a drum. Since GaAs has piezoelectricity*6, the membrane vibration (ultrasound phonons) can be induced by applying an alternating current (AC) voltage to electrodes placed on the membrane. This elastic vibration propagates along the waveguide and affected by the elastic potential created by the periodic holes, which modulates the dispersion relation. **Figure 2(b)** shows the dispersion relation obtained from numerical calculations (top) and the frequency response of the phonon transmission measured in the device (bottom). In the dispersion relation, the first phononic band (orange) is formed from 3.5 to 7.4 MHz, which guides phonon vibrations in the waveguide. As a result, it is confirmed that the vibrations excited from one end of the waveguide are observed at the other end. The band reaches the Brillouin zone edge at 7.4 MHz ($k = \pi/a$, k is wave number), and the gap shown in gray appears before the next band (light blue) emerges. This is the band gap. The half λ exactly matches a ($\lambda/2 = a$), so the phonon vibrations exhibit Bragg reflections*7 at the hole locations. The phonon propagation is significantly suppressed at the bandgap spectral position. Moreover, the generation of the band gap allows a gradual decrease in the phonon-propagation speed (group velocity) because the slope of the dispersion curve becomes gentle. The measured group velocity as a function of frequency is shown in **Fig. 2(c)**, which reveals that the propagation speed increases with frequency up to 7.0 MHz but then decreases beyond that frequency. Thus, we succeeded in experimentally observing the band gap and modulation in the group velocity, providing proof of a phononic crystal in our device.

*6 Piezoelectricity: A phenomenon that causes distortion when a voltage is applied to an object. In electromechanical phononic crystal, this strain causes bending moments, thus induces flexural vibrations in the vertical direction of the membrane.

*7 Bragg reflection: A phenomenon in which strong interference and reflection of waves appear when they are incident at an angle θ on a lattice plane in which atoms are periodically arranged, and the wavelength (λ) and lattice constant (a) satisfy Bragg conditions ($n\lambda = 2a\sin\theta$, n is a natural number.). In a one-dimensional system, $\theta = \pi/2$.



(a) Schematic of compression of a phonon wave packet with positive chirp (C >1). The frequency of the waves increases with time.

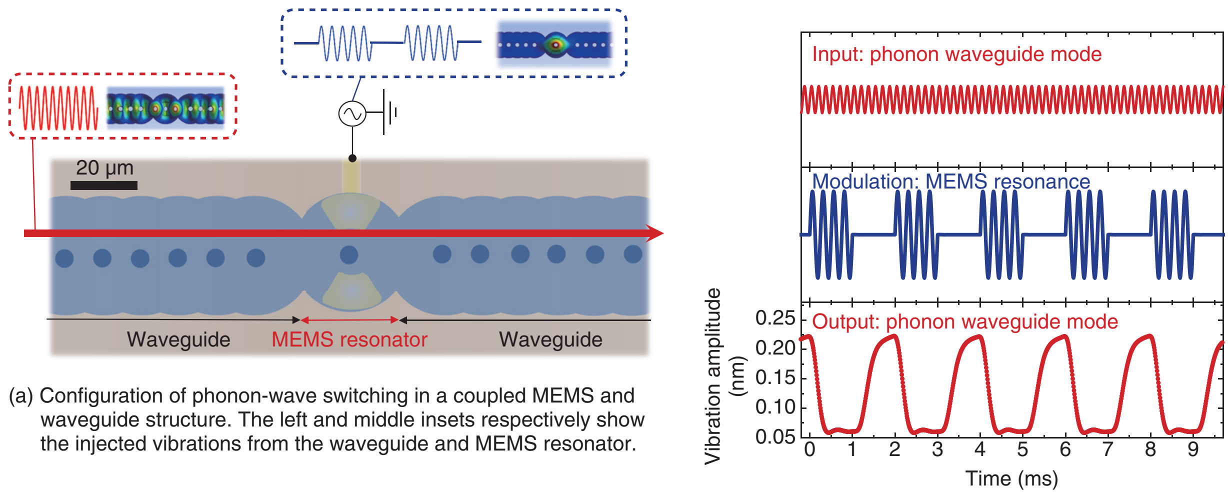
(b) Temporal width of propagating wave packets with various chirp constants (C) as function of propagation distance

Fig. 3. Waveform change by group-velocity dispersion.

4. Phonon-wave-packet engineering

The enriched properties of a phononic crystal enables us to control the phonon wave packets. Our device hosts group-velocity dispersion, in which the propagation speed varies with frequency. The envelope of a wave packet (pulse) has a finite temporal width and contains various frequency components near a phonon carrier frequency. Therefore, the waves in the packet travel with different speeds due to the group-velocity dispersion, resulting in expansion of the envelope. Although such waveform broadening and distortion are undesirable effects for stable waveguiding, we used them to demonstrate wave-packet control for pulse broadening and compression in this device.

A phonon wave packet with negative frequency modulation (negative chirp, $C < 0$) is injected from one end of the waveguide. The sign of the chirp constant (C) determines whether the frequency increases or decreases with time. If the carrier frequency is set to 5.8 MHz, the phonon with higher frequency propagates faster than the one with lower frequency in the waveguide (see Fig. 2(c)). In a negative chirp, the waves with higher frequency are located in the leading parts of the wave packet, and those with lower frequency are in the tailing parts of the wave packet at the input. Therefore, the high-frequency waves move forward, and the low-frequency ones are further delayed during the propagation, resulting in further expansion of the wave packet. When a positive chirp is injected as input, however, where the positions of lower and higher frequency waves are swapped, the wave packet is compressed during the propagation (**Fig. 3(a)**). **Figure 3(b)** shows the propagation-distance dependence of wave-packet width with various chirp constants (C). As described above, the pulse width monotonically increases with distance for negative chirp at $C = -3$, while it decreases for positive chirp at $C = 3$. However, the pulse changes from compressed to broadened at 7 mm then keeps broadening. This is because the initial distribution of the waves with different frequencies, caused by the input chirp, is fully eliminated at 7 mm. This compression effect is also enhanced by increasing the frequency-sweep range. When the chirp constant is increased from $C = 3$ to 9.7, the wave packet is strongly compressed from 2 to 0.6 μs. The observed minimum value is limited by the time constant of the bandpass filter in the measurement system. Therefore, the unique dispersion relation of a phononic crystal can be used to control the waveform of the propagating phonons. In this experiment, a chirp signal was used as an input, but it is also possible to achieve compression and expansion of the unchirped wave packet by the nonlinear effect, as described later [5].



(a) Configuration of phonon-wave switching in a coupled MEMS and waveguide structure. The left and middle insets respectively show the injected vibrations from the waveguide and MEMS resonator.

(b) Phonon-wave switching. Phonon transmission is temporally suppressed when the MEMS resonance is driven.

Fig. 4. Dynamic control of phonon waves in electromechanical phononic crystal.

5. Switching of phonon propagation

Dynamic control of phonon waves can also be carried out using MEMS characteristics in electromechanical phononic crystal [3]. We installed a membrane resonator in the center of the waveguide, which is used as the external modulation node (**Fig. 4(a)**). This membrane can behave as a single MEMS resonating around 2 MHz because of the weak coupling with adjacent membranes. Therefore, by applying an AC voltage to an electrode placed on the surface, resonant vibrations can be excited that are spectrally and spatially isolated from the phonon waveguide modes. When the membrane is strongly excited, the stress distribution inside it is readjusted due to the large vibration amplitude. As a result, the transmission dynamics of the phonon waves passing through the center membrane is also affected by this elastic modification; thus, the transmission spectrum changes. By appropriately adjusting the frequency of the phonon waveguide mode, the transmission intensity can be reduced. **Figure 4(b)** shows the temporal response of the transmitted amplitude of the phonon waveguide mode measured at one end. It is excited by continuous waves at 5.745 MHz from the other end, and simultaneously the resonant vibration of the membrane at 1.855 MHz is periodically generated at an interval of 1.0 ms. The propagation amplitude decreases only when the central membrane vibrates. Thus, by using the enriched nonlinearity of the MEMS structure, the dynamic control of the phonon wave propagation is achieved in electromechanical phononic crystal.

This nonlinear MEMS technology enables a variety of phonon controls, such as vibration energy transfer, all mechanical random-access memory operation, and frequency conversion of propagating phonon waves on this chip-scale platform.

6. Ultrahigh-frequency phonons and fusion with magnons

With electromechanical phononic crystal, we can achieve spatial and dynamic control of phonons on a chip. However, the operation frequency is as low as a few megahertz, so it is necessary to increase it up to the gigahertz band (hypersound) for practical use in, for instance, wireless communications devices. We have succeeded in fabricating a phononic crystal device operating at ultrahigh frequencies [6]. We have also explored the possibility of dynamically controlling hypersonic phonons using ferromagnetic spin waves called magnons. Combining the hypersonic structures and magnons with the electromechanical-phononic-crystal technology described in this article holds promise for the development of phononic active devices operating at ultrahigh frequencies and integrated hypersonic circuits, which will dramatically enhance the availability of phonons as information carriers.

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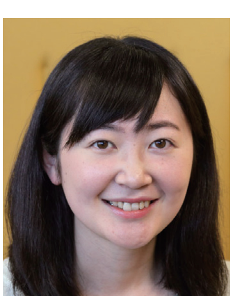

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Development of an Optomechanical Device with Extremely Low Optical Energy Loss

Ryuichi Ohta, Victor M. Bastidas, Hiroshi Yamaguchi, and Hajime Okamoto

Abstract

Optomechanical devices have attracted attention as functional devices that add mechanical degrees of freedom to optical devices such as light-emitting ones. Optomechanical devices have mainly been constructed of semiconductor materials that are easy to microprocess, but NTT laboratories are developing optomechanical devices composed of rare-earth materials that have optical properties superior to those of semiconductors. In this article, we introduce research results on an optomechanical device with extremely low optical energy loss, which was achieved using erbium ions with a luminescence lifetime much longer than that of semiconductor materials.

Keywords: erbium, strain engineering, optomechanical device

1. Optomechanical devices using erbium ions

A cantilever structure made of a thin semiconductor film such as silicon is a nanomechanical device[*1] that uses the vertical vibration of the film. Such devices are used in a wide range of applications, such as for micro sensors used in mobile terminals and cutting-edge analytical equipment. These devices are roughly divided into electromechanical devices that can be electrically operated and optomechanical devices that can be operated by light. In the latter, the interaction between light and mechanical vibration can be enhanced by confining light and vibration in the same region [1]. Therefore, optomechanical devices are attracting attention as devices that enable highly sensitive vibration detection and high-precision vibration control through the interaction between light and motion.

The relationship of energy-loss time between light and mechanical vibration is important for optomechanical devices. Energy-loss time refers to the time it takes for light to lose energy and become dark, and mechanical vibration refers to the time it takes for the vibration to lose energy and stop. We can control a physical system with a longer energy-loss time by using another physical system with a shorter energy-loss time. For example, if light lasts longer than vibration, vibration can be used to modulate the intensity and phase of light. In contrast, when vibration lasts longer than light, it is possible to control vibration by using light. In conventional optomechanical devices made of semiconductor materials, the lifetime, or energy-loss time, of light is much shorter than that of mechanical vibration, making it possible to control vibration using light [2], but it has been difficult to control light using vibration. To address this issue, NTT laboratories have developed

*1 Nanomechanical device: An artificial structure in which mechanical vibration is continued by periodically executing elastic deformation. The diaphragm of musical instruments, such as bells and harps, is also a type of mechanical device. Recent advances in microfabrication technology have made it possible to integrate mechanical devices, which are thinner and smaller than a human hair, into semiconductor chips. One of the most typical shapes of nanomechanical devices is the cantilever, which is what we used in this study; it has a shape similar to a swimming pool diving board.

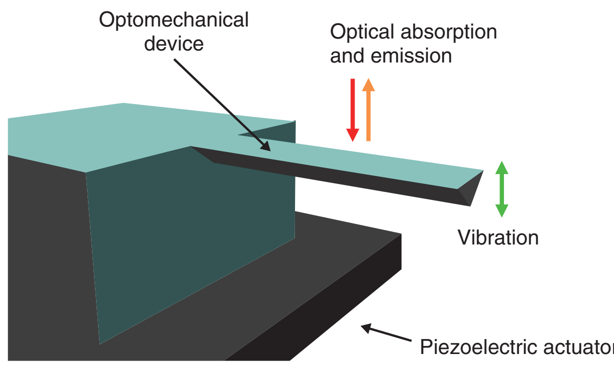

Fig. 1. Schematic image of an optomechanical device containing erbium ions. Both sides of the region used for the optomechanical device were scraped off by oblique milling of ion beams to create a cantilever structure with an inverted triangular cross-section. A large amount of erbium ions is embedded in the device, which is affected by the strain caused by mechanical vibration. By irradiating erbium ions with resonant light, it is possible to investigate the optical-absorption characteristics stemming from the strain.

an optomechanical device in which the energy-loss time of light exceeds the loss time of vibration thanks to the use of erbium ions, which has a significantly longer emission lifetime compared with semiconductor materials [3]. This enables novel applications such as optical amplification and oscillation using mechanical vibration, which were previously difficult to achieve experimentally.

Since erbium can absorb and emit light in the communication-wavelength band (about 1.5 µm) suitable for long-distance transmission, it has been applied to lasers and optical amplifiers for optical communication. Therefore, if erbium is used for optomechanical devices, the devices can be operated in the communication-wavelength band. Also, as mentioned above, erbium is a material with a long emission lifetime and low energy loss, so the use of erbium is expected to save energy in such devices.

2. Modulation of erbium resonance wavelength by mechanical vibration

Many optical materials (e.g., semiconductors and erbium) produce strong light absorption and emission at resonance wavelengths. The resonance wavelength depends mainly on the properties of the material and on external factors such as electric and magnetic fields. In the optomechanical device used in our study, strain can be introduced as an external factor by mechanical vibration. Optomechanical properties, in which the resonance wavelength of erbium is modulated by distortion, enable vibration detection by using light and light control by using vibration. However, the optical resonance of erbium is not very sensitive to strain because the energy levels that contribute to resonance are present in the core region of the atom. Our optomechanical device can locally apply large strain by using the resonance characteristics of the mechanical element. Resonance is a phenomenon in which vibration is amplified at a frequency inherent to the device. Since the quality (Q) factor of the mechanical resonance of our device is 2500, we can introduce a strain approximately Q times larger, that is, about 2500 times larger, than a device without resonance. We succeeded in modulating the resonance wavelength of erbium by introducing a large strain using mechanical resonance.

In our optomechanical device (**Fig. 1**), a large ensemble of erbium atoms is embedded in a crystal. This crystal is milled obliquely with a focused ion beam[*2] to obtain a cantilever with an inverted triangular cross-section (length: 140 µm, width: 14 µm, maximum thickness: 7 µm). The device is placed on a piezoelectric actuator and cooled to about 4 Kelvin (–269°C), where a sharp optical resonance of erbium can be obtained. The actuator is then used to excite the vibration of the device in this cryogenic environment. When an alternating current (AC) voltage is applied to the actuator, the actuator vibrates at that frequency. The chip of the device installed on the

*2 Milling method using ion beams: A method of physically scraping away material by bombarding it with ions released in a vacuum. It is characterized by its ability to process a variety of materials regardless of their composition. It is also possible to create three-dimensional structures such as nanomechanical devices by slanting ions.

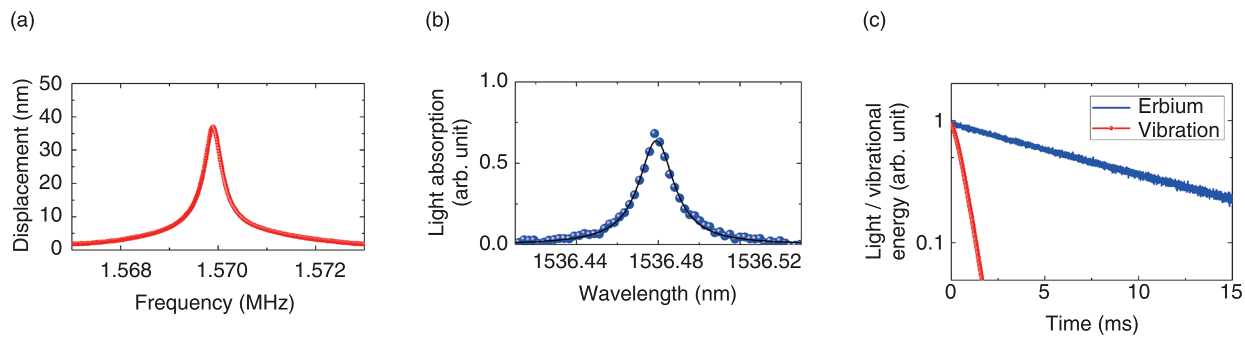

Fig. 2. (a) Relationship between vibration displacement and frequency of optomechanical element. The maximum displacement (vertical axis) occurs when the frequency of the AC voltage applied to the piezoelectric actuator (horizontal axis) matches the resonant frequency of the device (1.57 MHz). (b) Optical-absorption spectrum of the optomechanical device. There is a clear absorption peak originating from erbium ions at a wavelength of 1536.48 nm. (c) Temporal changes in the emission intensity of erbium (light energy) and the amplitude of the mechanical motion (vibrational energy). This confirms that the lifetime of light is much longer than that of vibration.

actuator also vibrates in the same manner, but when the frequency of the AC voltage matches the resonance frequency (1.57 MHz), mechanical resonance causes displacement of about Q times in the mechanical element. This vibration can be measured by irradiating a detection laser (wavelength: 633 nm) to the device and detecting the reflected light with a Doppler interferometer (**Fig. 2(a)**). During mechanical resonance, a large strain is applied near the central surface of the cantilever, and this strain acts on the erbium ions embedded in the crystal. We conducted an experiment to confirm the mechanical properties of the device then evaluated the optical properties by irradiating a tunable laser (wavelength: approximately 1536 nm = 1.536 μm) for optical excitation. **Figure 2(b)** shows the relationship between the laser wavelength and light-absorption intensity when the optomechanical device is not driven. A sharp peak based on the optical resonance of erbium can be observed at around 1536.48 nm.

One of the key features of this device is that the lifetime of erbium emission exceeds that of mechanical vibration. **Figure 2(c)** shows the experimental results that confirm this. In this experiment, the excitation of vibration by the actuator and the excitation of light by erbium were stopped simultaneously at a certain time, and from that moment, the intensity of light and amplitude of vibration were measured to determine how much they attenuated over time. The results indicate that the energy-loss time of light is sufficiently longer than that of vibration. Such a relationship cannot be achieved without the use of optical resonance, which has a very low energy loss, but we succeeded in achieving this by using erbium ions with better optical properties than conventional semiconductor materials.

Another important feature of this device is that the optical resonance of erbium changes in accordance with the vibration displacement of the device. This was confirmed through experiments to evaluate how the optical resonance in Fig. 2(b) responds to time when the frequency of the voltage applied to the actuator matches the mechanical resonance frequency (1.57 MHz). The results are shown in **Fig. 3**, where the horizontal axis represents the wavelength of light, the vertical axis represents time, and the intensity of color represents the optical-resonance intensity of erbium. We can see that the optical resonance of erbium shifts in accordance with the period of mechanical vibration (0.64 μs = reciprocal of 1.57 MHz (resonant frequency)). The amount of shift exceeds the optical linewidth of erbium, which confirms that erbium emission can be controlled using strain.

3. Amplification and oscillation of light using mechanical vibration

The above phenomenon, in which the resonance wavelength of erbium changes in response to vibration, is based on the nonlinear interaction between light and mechanical vibration. This nonlinear interaction is what makes it possible to construct nonlinear optomechanical devices such as optical amplifiers. **Figure 4** shows how the emission intensity of erbium is amplified in accordance with the pump-light

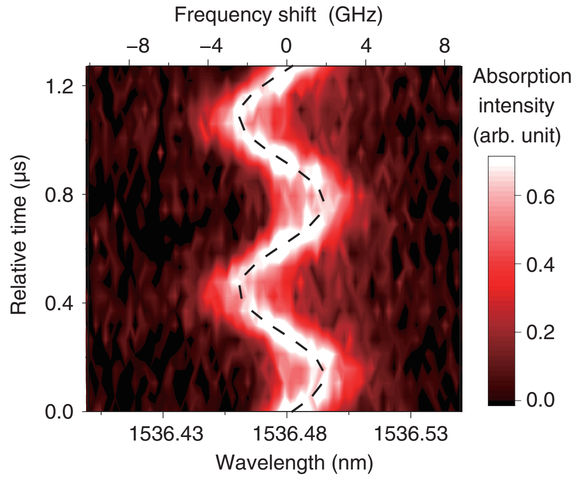

Fig. 3. Time dependence of optical-absorption spectra in an optomechanical device when vibrations are excited within a certain mechanical-resonance period (0.64 µs). The absorption wavelength of erbium ions changes sinusoidally with the period of mechanical resonance. The dotted line shows the change in the center wavelength.

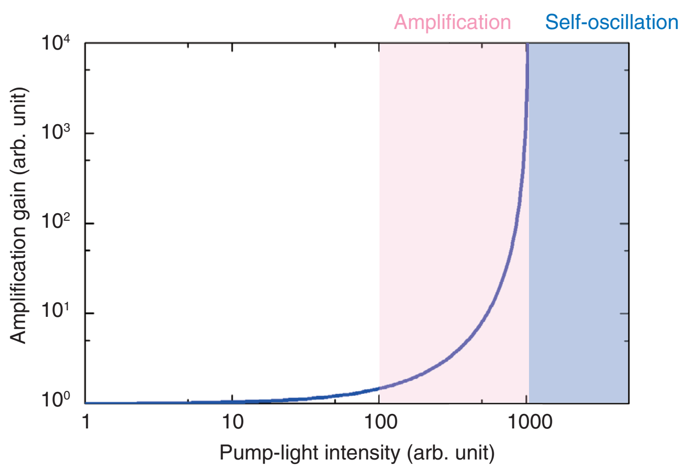

Fig. 4. Simulation results showing the relationship between the optical-signal amplification gain and pump-light intensity when the device is irradiated with pump light that matches the sum of the resonance frequency of erbium ions and mechanical resonance frequency. As the pump-light intensity increases, the amplification gain of light increases (pink region), and when the threshold value is exceeded, self-oscillation (blue region) is observed.

intensity when pump light is introduced into the optomechanical device. In this simulation, we used the magnitude and loss time of the interaction between light and mechanical vibration obtained from the above experiment. When the frequency of the pump light matches the sum of the resonance frequency of erbium ions and the mechanical resonance frequency, the light can be amplified and oscillate. This is because the energy of the pump light is distributed to the energy of optical resonance and mechanical resonance under such frequency-matching conditions. However, the energy distributed to mechanical resonance is lost much faster than that of optical resonance, so the energy can be selectively supplied to the optical resonance. This is a unique phenomenon that can be achieved with this optomechanical device, in which the lifetime of light is much longer than that of mechanical vibration. Such a mechanically induced optical amplifier formed on a chip is attracting attention as a compact and energy-saving optical device.

Since the gain obtained depends on the structure of the mechanical properties and Q factor, even higher gains can be expected in the future by optimizing the device structure.

4. Summary and future outlook

This article introduced an optomechanical device we developed using rare-earth materials. By embedding erbium ions in a crystal, which have a lifetime longer than that of mechanical vibration, we have shown that optical resonance-frequency control and signal amplification can be achieved using this optomechanical device. We conducted our experiments in the very low temperature environment of –269°C. For future work, we will improve the materials and structures for operation at which nitrogen is in liquid phase (–196°C) and develop devices that can be practically applied. The operating frequency of the present device is about 1 MHz, but we aim to achieve high-speed operation in the GHz range by miniaturizing the device. If such high-speed operation can be attained, applications to optical-control technologies such as modulation of a laser light and wavelength multiplexing should be possible. Erbium is a material that can be used not only for optical communication but also for quantum information. Therefore, application of optomechanical devices containing erbium ions to quantum information technology is expected in the future.

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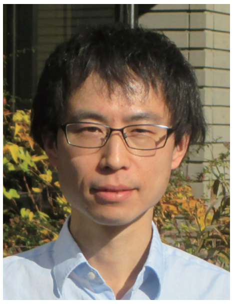

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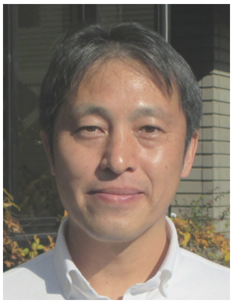

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Highly Sensitive Detection and Control of a Nanowire Mechanical Resonator Using an Optical Microcavity

Motoki Asano, Guoqiang Zhang, Hiroshi Yamaguchi, and Hajime Okamoto

Abstract

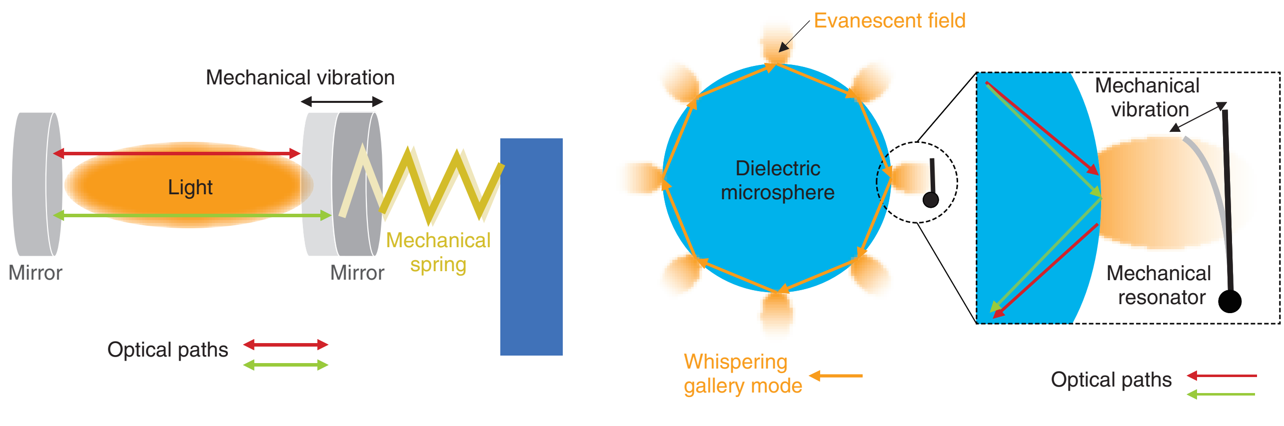
Semiconductor nanowires have a rod-like structure that is too thin to be seen by the naked eye. This fine structure strongly confines photons and electrons, enabling us to use quantum nano-optoelectric properties to control photons and electrons individually. Semiconductor nanowires also function as nanomechanical resonators when their flexural motion is available. To achieve new opto-electro-mechanical hybrid quantum devices, NTT laboratories have developed technology to detect and control nanowire mechanical motion with high sensitivity.

Keywords: optical microcavity, nanowire, mechanical resonator

1. Semiconductor nanowire as hybrid mechanical device

A semiconductor nanowire is a very thin rod with diameters of hundreds of nanometers (about 1/100 the width of a strand of hair) and lengths of a few micrometers. If you compare a semiconductor chip of a few millimeters square to the size of a tennis court, a nanowire would look like a toothpick standing upright on the court. Therefore, it is difficult to see the whole picture with a light microscope as well as with the naked eye. Even with such a small structure, it is possible to confine photons and electrons inside it using the latest semiconductor technology. NTT laboratories are conducting basic research for the application of semiconductor nanowires to optical and electronic devices such as ultralow-power semiconductor lasers and spintronics devices capable of controlling electron spin. In addition to such quantum optoelectric properties, semiconductor nanowires have the functions of nanomechanical devices with excellent mechanical properties. For example, a nanowire grown perpendicular to a substrate can be used as a nanomechanical resonator because it shows resonant flexural motion. Since this nanomechanical resonator has a very small structure, its vibration characteristics are significantly modified by external forces and additional mass due to adhesion of small objects on the resonator. By using this ultrasensitive feature, a nanomechanical resonator can be used as a mechanical sensor to detect external forces and nano/micro particles by reading the changes in its vibration characteristics. It can also be utilized as a mechanical actuator driven by light or electricity. Thus, various studies have investigated the characteristics of nanowires used as nanomechanical resonators [1].

Attempts to develop a hybrid device with optical, electrical, and mechanical properties, using a semiconductor nanowire have just begun. Such innovative hybrid devices would enable us to implement new information processing using a combination of optical, electrical, and vibration signals, and control



(a) Cavity-optomechanical setup with a mirror cavity connected to a mechanical spring

(b) Near-field optomechanical setup with a dielectric microsphere approaching a mechanical resonator

Fig. 1. Conceptual illustration of cavity optomechanics and near-field optomechanics.

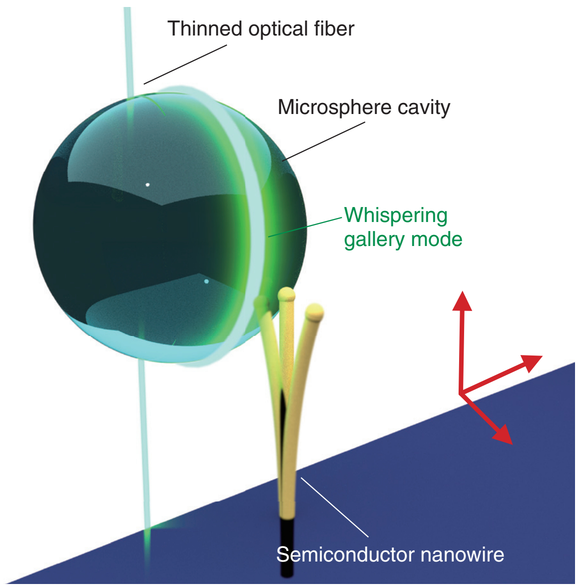
optical and electrical material properties with vibration. Bringing them into an extreme region, where quantum mechanical properties of photons, electrons, and phonons appear, will accelerate the quantum information technology through the development of novel quantum light sources and quantum memories. Such hybridation will pave the way to creating innovative quantum opto-electro-mechanical devices [2].

Although semiconductor nanowires are strong candidates for developing such a hybrid quantum device, the technology for detecting and controlling tiny mechanical vibrations has not been sufficiently developed. The main issue originates from the size of the nanowires, which are too small to be seen directly. The conventional laser-irradiation technique, which is used to detect vibrations in solid-state nanomechanical devices that are barely visible, is not suitable to resolve a nanowire structure smaller than the wavelength of light (about 1 μm). Therefore, we need to develop new and effective methods for detecting and controlling extremely small nanowire mechanical motion. The following is a brief introduction to near-field cavity optomechanics, which was recently developed by NTT laboratories using a small glass sphere as a new technology for ultrasensitive vibration detection and control of semiconductor nanowires [3].

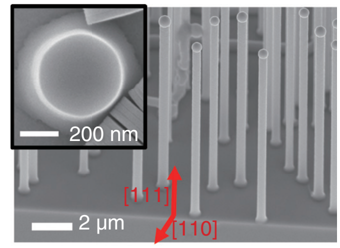
2. Near-field optomechanics using a glass microsphere cavity

The mechanism of cavity optomechanics can be understood in a model of a mirror cavity with one side connected to a mechanical spring, as shown in **Fig. 1(a)**. The cavity is a box that strongly confines light. In this model, light is confined by reflection back and forth between two mirrors. When the mechanical spring attached to the mirror vibrates, the path of light confined in the cavity changes. Since light has the properties of a wave, this path change is represented by a change in the optical phase of the wave. By reading this optical-phase change, vibration of the mechanical spring can be detected with high sensitivity. When light strongly confined in the cavity is reflected by the mirror, however, a force is applied to the mirror as a backaction that changes the momentum of the light. This force (radiation pressure) can be used to drive mechanical springs and control their resonance frequency.

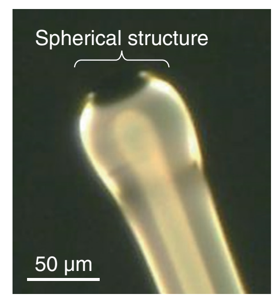
The radiation pressure of light was discovered in the tail of a comet in ancient times, but it was not until the early 2000s that cavity optomechanics flourished as an applied technology. State-of-the-art optomechanical devices have successfully detected and controlled quantum fluctuations corresponding to a single vibrating quantum particle (i.e., a single phonon). However, applying such cavity optomechanics to



(a) Conceptual illustration of near-field optomechanical setup



(b) Electron-scanning-microscope image of semiconductor nanowires (the red arrows show the crystal axes)



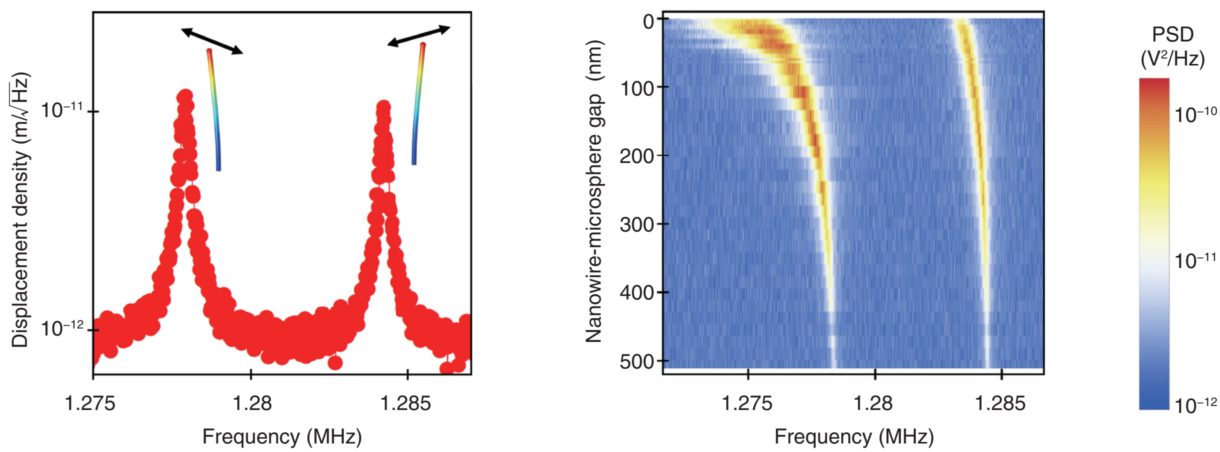
(c) Optical microscope image of silica microsphere cavity

Fig. 2. Experimental setup and device structure.

semiconductor nanowires, which are extremely small structures, is difficult. This is because it is not easy to fabricate nanowires produced using special growth techniques and high-quality optical cavities on the same chip. Even if large cavities such as mirror cavities are installed externally, it is difficult to generate sufficient optomechanical coupling to such small nanowires.

We demonstrated, for the first time, near-field optomechanics with a microsphere approaching semiconductor nanowires. The optical microsphere cavity, the key to this technology, is fabricated independently of semiconductor nanowires by processing transparent glass called silica glass, which is also a well-known material for optical fibers. Just as glassworkers make glass cups and wind chimes, very small glass balls of several tens of micrometers in diameter can be made by heating and inflating the tips of silica optical fibers. When a thinned optical fiber is brought into contact with this glass ball, a cavity-optical mode called the whispering gallery mode is induced in which light leaked from the optical fiber circularly travels across the glass ball's surface. In this case, as shown in **Fig. 1(b)**, there is an evanescent field with finite optical leakage to the outside of the sphere due to the total reflection. When the evanescent field is brought close to the nanowire, the path of the light (i.e., optical phase) around the cavity changes in response to the nanowire vibration. This change in the optical phase makes it possible to detect the vibration. As in the mirror cavity example, this induces backaction forces to the nanowires. By using this interaction between light and mechanical motion, nanowire mechanical motion can be controlled by laser light. This near-field cavity-optomechanical technique with the optical evanescent field enables highly sensitive detection and control of nanowire vibrations smaller than the wavelength of light.

The experimental setup is depicted in **Fig. 2(a)**. The measurement uses one of the InAs/InP (indium arsenide/indium phosphide) heterostructure semiconductor nanowires (14-μm long, 500 nm in diameter; **Fig. 2(b)**) grown in great numbers on an InP substrate. The optical cavity is a 40-μm-diameter glass ball fabricated via electrical discharge processing on an optical fiber tip (**Fig. 2(c)**). The whispering gallery mode is induced by contacting a communications-wavelength optical fiber thinned to about 1 μm with the glass ball. By bringing the evanescent field of this mode close to the nanowire, we observed an optical



(a) Displacement density of semiconductor nanowire
The insets show the flexural motion of the nanowire.

(b) Power spectral density (PSD) with respect to the nanowire-microsphere gap

Fig. 3. Results of highly sensitive displacement measurement and vibration control.

resonance with a quality (Q) factor of 1.8×10^5. The Q factor is a quality measure of how strongly light can be confined in the cavity, and 10^5 refers to highly confined optical resonance classified as having a high Q factor.

3. Sensitive displacement measurement and vibration control of semiconductor nanowires

We constructed an optical measurement system called a homodyne optical interferometer to read out the change in the phase of light accompanied by the nanowire vibration with high sensitivity. The advantage of this interferometer is that the phase change of the light can be read with high sensitivity, which is different from the usual detection method for detecting optical power. When spectral measurements were carried out on the interferometer output signal, two peaks were observed near 1 MHz (**Fig. 3(a)**). These peaks correspond to the thermal fluctuations of the nanowire mechanical modes in both the vertical and horizontal directions. Thermal fluctuations are vibrations in which the nanowires move randomly depending on the ambient temperature, and the higher the temperature, the greater the fluctuation. The thermal fluctuation of the nanowires used in this experiment at room temperature was about 100 pm (~ 1×10^{-11} m/Hz$^{0.5}$, which is the same size as one atom), and the minimum detectable displacement (corresponding to the floor level in Fig. 3(a)) was found to be about 10 pm. This minimum detectable displacement corresponds to the amount of thermal fluctuation expected when the nanowires are placed in an environment of 2.8 K. This indicates that the nanowire-thermal fluctuation can be detected even in a very low temperature environment of about –270°C, which is near absolute 0. In such a cryogenic environment, electrons confined in semiconductor nanowires exhibit quantum mechanical properties. Therefore, if we can extract the mechanical freedom of nanowires in such an environment, we will make great progress toward hybrid quantum devices.

It is important not only to detect vibrations but also to develop technologies to actively control them. Our technique based on near-field cavity optomechanics with a small glass sphere can detect the vibration of the nanowire and simultaneously control the vibration with laser light. This is the same principle as the optical gradient force applied in optical tweezers. The force acts on the object from the lower to higher density of the optical electric field. This force increases as the gap between the cavity and nanowire decreases, causing a change in vibration frequency and increase in linewidth (**Fig. 3(b)**). We have also succeeded in using this force to rotate the vibration axis of the nanowires, although the details are omitted here. Therefore, we found that the vibration characteristics of nanowires can be precisely controlled using the strong optical gradient force in the microsphere cavity.

4. Future prospects

The technology introduced in this article enables highly sensitive detection and control of mechanical motion in semiconductor nanowires that are smaller than the wavelength of light. The detection sensitivity is expected to be further enhanced by improving the Q factor of the optical cavity. The Q factor of the optical cavity used in the above experiment was about 10^5, but it is also possible to obtain a Q factor of 10^7 or more by machining with better accuracy. It has been theoretically predicted that such a high Q factor can increase the detection sensitivity to the level of not only thermal fluctuations but also quantum-mechanical fluctuations, which are two orders of magnitude smaller than thermal ones. Although there are still many problems to be solved experimentally, we will continue our research on semiconductor nanowires for innovative hybrid quantum devices.

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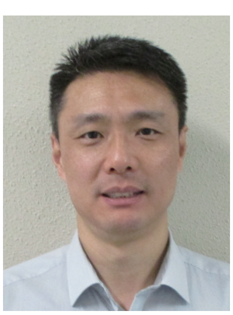

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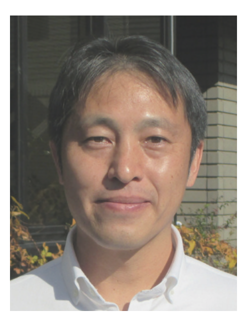

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Fabrication of Suspended Nanowire Mechanical Devices Using Inkjet Technology

Satoshi Sasaki, Kouta Tateno, Hajime Okamoto, and Hiroshi Yamaguchi

Abstract

Semiconductor nanowires are attracting attention as building blocks for next-generation electrical and optical devices. When nanowires are suspended, they function as nanomechanical devices with specific mechanical properties, thus are expected to be applied to high-sensitivity sensors. This article explains how such a nanomechanical device can be easily and efficiently fabricated using inkjet technology while minimizing resource waste.

Keywords: nanowire, inkjet, nanomechanical device

1. Inkjet printers

Inkjet printers are common household electrical appliances used for printing from personal computers to paper. They are also used in various industrial fields to, for example, print characters on three-dimensional objects, such as dates on plastic bottle caps. Such three-dimensional printing is possible because the printer head does not directly contact the object on which characters or pictures are to be printed. There are two main types of ink-ejection methods for conventional inkjet printers. One is the piezo method, which pushes out ink by pressure, and the other is the thermal method, which pushes out ink by heating. The minimum size of a droplet ejected from a home inkjet printer is approximately 1 pL, and the diameter of a droplet moving through the air is said to be approximately 10 µm. However, the actual minimum printing resolution is several tens of micrometers, because the droplet spreads slightly from the time it reaches a printing object such as paper until it dries.

Inkjet printers can not only print characters and pictures on paper but can also directly "print" electronic circuits just like those on printed circuit boards. Because the inkjet printers can arrange materials such as metal electrodes without a photomask and do so on demand, thus, it can be applied to microstructure formation on soft organic materials that are incompatible with conventional top-down methods such as photolithography. The inkjet method can also be applied to flexible electronic devices that can be attached to living tissue such as human skin. When a metal pattern is formed using the conventional lift-off method, a large amount of material is wasted because only part of the deposited metal is left on the substrate as electrodes and wiring; the majority is removed together with the photoresist. However, with the inkjet method, only the necessary amount of material can be placed on demand at the desired location. This is advantageous from the viewpoint of saving resources.

2. Nanomechanical device using semiconductor nanowire

Our research group has mainly studied mechanical devices on the micrometer scale. We focus on semiconductor nanowires as mechanical vibration elements with a cross-sectional size on the nanometer

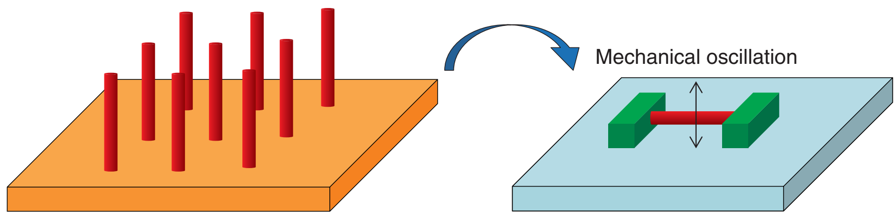


Fig. 1. Schematics of as-grown nanowires and mechanical oscillation device.

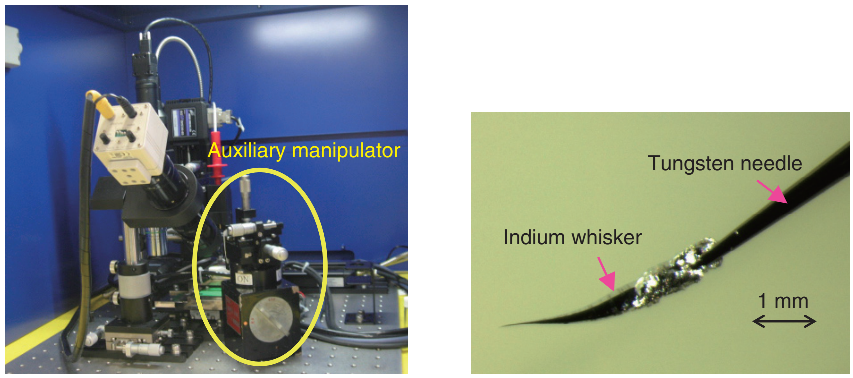
scale. As schematically shown in **Fig. 1(a)**, nanowires are whisker-shaped crystals that are grown at an angle along a certain crystallographic orientation with respect to a semiconductor substrate. They are typically a few hundred nanometers in diameter and about ten micrometers in length. Although nanowires as grown on the substrate can be processed into devices such as lasers and transistors (vertical devices), we decided to transfer nanowires to another device substrate, as shown in **Fig. 1(b)**, to fabricate a horizontal doubly clamped beam structure for better control of the mechanical properties. We use indium arsenide (InAs) as the semiconductor material because electrons accumulate on the surface and good electrical contact can be obtained.

The most primitive means of transferring nanowires from a growth substrate to another substrate for fabricating nanomechanical devices is to rub a piece of the growth substrate against the device substrate or take up some nanowires on a cotton swab and press them on the device substrate. With this method, however, the positions where the nanowires are transferred on the device substrate are determined entirely by chance. If we retrofit the electrodes to the location of the nanowire, we may find a nanowire that can be used somewhere on the device substrate. However, we cannot rely on chance because we need to suspend the nanowire over a pre-patterned groove, as explained later. Even if a nanowire is accidentally transferred to the desired position, most of the other nanowires are not used and are wasted. To avoid such inefficiency and waste, it is necessary to place the nanowires at predetermined positions on the device substrate while observing them in real time with an optical microscope. A resin film, such as electron-beam resist, is often used to pick up small pieces of thin films, such as graphene, and transfer them to another substrate. Although this technique can be applied to nanowire transfer, we developed a method using an inkjet printer for more efficient transfer. We used a high-specification machine dedicated for research purposes that can eject ultrafine droplets that are about 1/1000 the size of droplets from household inkjet printers [1]. The discharge method is an electrostatic one that differs from the two common methods described above. Although the machine is larger than a household inkjet printer, it is still desktop size and can be operated relatively easily under normal temperature and pressure.

3. Fabrication of nanowire mechanical device by using inkjet method

Figure 2(a) shows a photograph of the main part of the actual inkjet machine (manufactured by SIJTechnology). The inkjet nozzle is located under the red cylindrical part that can be seen at the back of the observation camera, enabling precise control along the X, Y, and Z axes. We added our developed auxiliary manipulator. As shown in the enlarged photograph in **Fig. 2(b)**, a thin whisker of indium (a few micrometers in tip diameter) is attached to the tip of a tungsten needle and used to finely adjust the position of the nanowires once they have been inkjetted onto the device substrate [2].

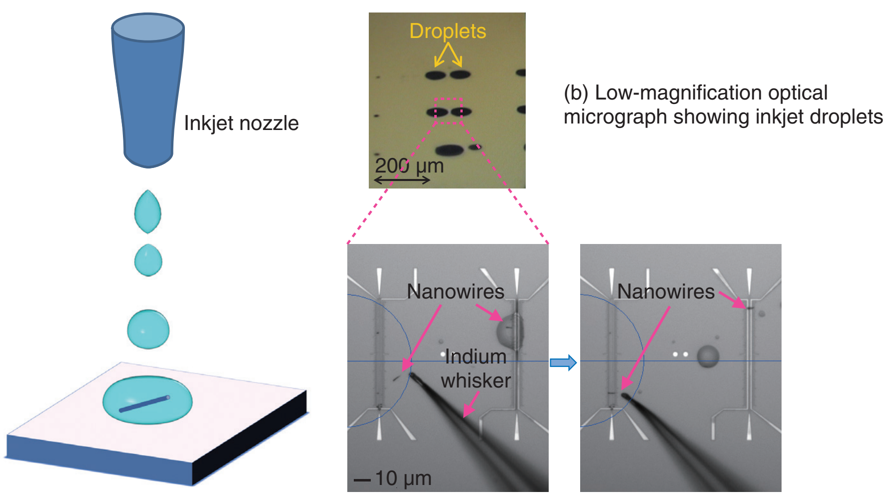
In actual transfer operations, nanowires are dispersed in a slow-evaporating solution called butylcarbitol, which is then filled into an inkjet machine as "ink." A sufficient number of nanowires can be dispersed by brushing off nanowires from a small area of a few millimeters in the growth substrate with a thin brush. **Figure 3** shows a schematic diagram of the process of ejecting droplets of butylcarbitol solution containing nanowires as well as optical microscope photographs taken during an actual transfer operation. As shown in Fig. 3(b), butylcarbitol droplets are



(a) Central part of the inkjet machine

(b) Tip of the auxiliary manipulator

Fig. 2. Inkjet printer and our developed auxiliary manipulator.



(a) Schematic of inkjet ejection of droplets containing nanowires

(c) High-magnification optical micrograph of nanowire-manipulation process

Fig. 3. Inkjet-transfer process of nanowires.

ejected into several areas that appear as black ellipses in a low-magnification optical micrograph viewed from an oblique direction. To transfer nanowires with a length of about 10 μm, a nozzle with a relatively large diameter is used. Therefore, considerably large droplets for this inkjet machine (a little less than 50 μm in diameter) are ejected. As shown in the high-magnification optical micrograph in Fig. 3(c), two sets of right and left microelectrodes are formed beforehand on a silicon (Si) substrate, and droplets are ejected aiming at each electrode group. The evaporation of butylcarbitol progresses, and the droplets almost disappear, but the nanowires are not completely fixed to the substrate yet. From the photo on the left in Fig. 3(c), the concentration of the nanowire dispersion is adjusted so that each droplet contains one nanowire, but the nanowire does not yet sit on the electrodes due to the large original droplet size. The position of the nanowires is then adjusted with the auxiliary manipulator of whiskered indium, as shown in the right photo of Fig. 3(c), where each nanowire is found on top of and perpendicular to the electrodes. At this time, the nanowire is moved together with each droplet, or a solution is left between the nanowire

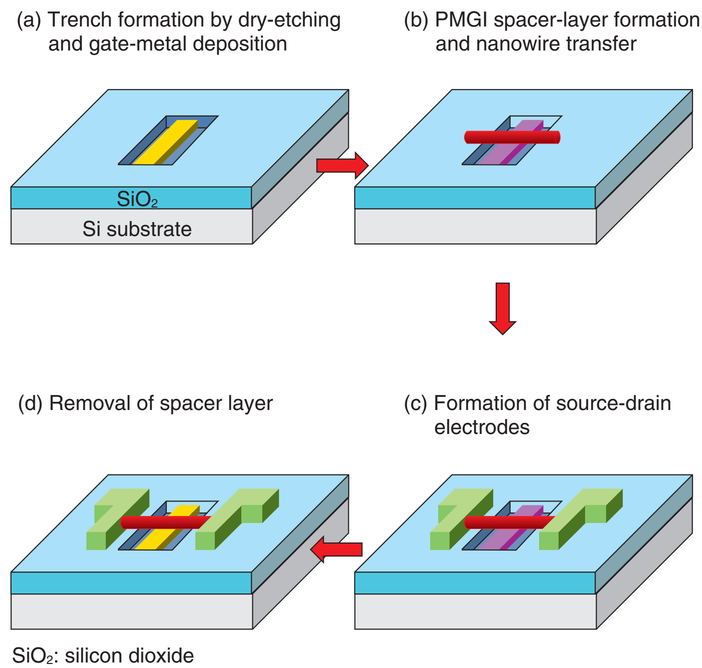


Fig. 4. Fabrication flow of a suspended nanomechanical device.

and the substrate, so that no excessive force is applied to the nanowire. Even if the tip of the manipulator directly touches the nanowire, it will not damage the nanowire because indium is soft metal. By using the auxiliary manipulator in this manner, the nanowire can be finally positioned with an accuracy of about 1 µm.

Figure 4 shows the flow for fabricating a nanomechanical device. First, a trench is dry-etched into a surface oxide layer on a Si substrate, and back-gate metal for electromechanical control is deposited in the trench. The final difference between the trench depth and gate-metal thickness is the distance between the nanowire and gate (approximately 300 nm). If the nanowire is transferred directly above the gate metal with an air gap, it will be pulled down and come into contact with the gate surface in the lift-off process, preventing free mechanical motion. Therefore, the trench is first covered with a resin spacer layer called polydimethylglutarimide (PMGI), onto which the nanowire is transferred using the inkjet method. After the source/drain electrodes for electrical measurement have been formed by lithography and lift-off, the spacer layer is removed by isotropic ozone cleaning in the gas phase, and the fabrication of a suspended nanomechanical device is completed.

A scanning electron microscope (SEM) photograph of the fabricated nanomechanical device and schematic cross-sectional view are shown in **Figs. 5(a)** and **(b)**, respectively. The length of the vibrating segment of the nanowire is 10 µm, and the width of the back gate, which is electrostatically coupled to the nanowire via a 300-nm gap, is 4 µm. As shown in **Fig. 5(c)**, the signal from the mechanical vibration was detected by monitoring the current flowing between the source and drain electrodes while applying a high-frequency voltage to the gate electrode, which exerts an alternating electrostatic force on the nanowire. A Lorentzian-type resonance peak was observed at around 12.9 MHz, which is close to the resonance frequency calculated from the length and diameter of the nanowire, indicating that a suspended nanomechanical device was properly fabricated [3].

4. Future developments

The typical size of a semiconductor nanowire, 100 nm in diameter and 10 µm in length, is close to the minimum size that can be manipulated while observing it in real time with an optical microscope at room temperature and atmospheric pressure. Although the inkjet printer uses micrometer-scale technology, the gap between a micrometer-scale system and nanometer-scale one can be bridged via nanowires with

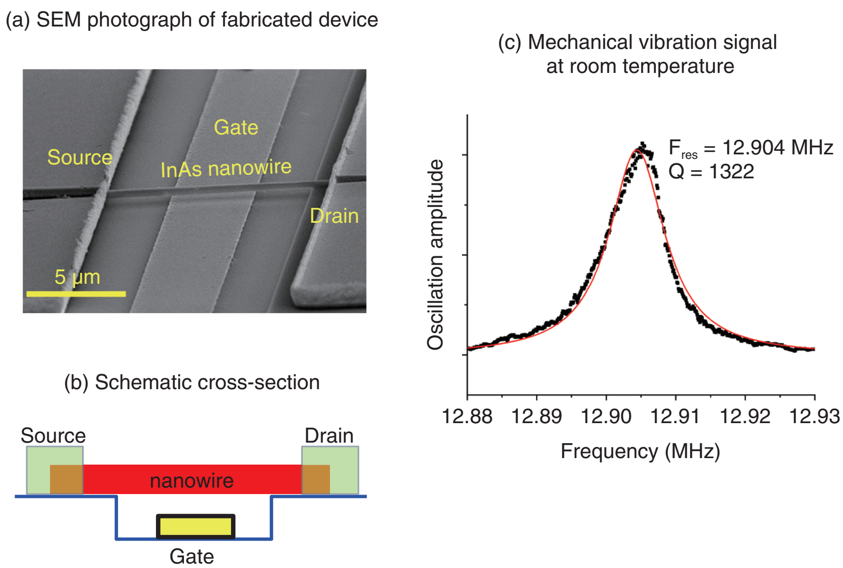


Fig. 5. Fabricated suspended nanomechanical device and observed mechanical resonance peak.

submicrometer diameters. As a result, applications can be expanded to regions with a higher resonance frequency and high-sensitivity sensors that can detect single molecules adsorbed on nanowires by reducing the mass of the beam structure.

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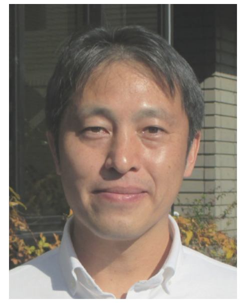

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High-speed Tunable Laser Based on Electro-optic Effect for Wavelength Switching

Yuta Ueda, Yusuke Saito, Takahiko Shindo, Shigeru Kanazawa, and Mitsuteru Ishikawa

Abstract

We developed a high-speed tunable laser, the lasing wavelength of which is tuned by the electro-optic (EO) effect of a semiconductor multi-quantum well. The laser exhibited a tuning range of 35 nm (full C-band), which is the world's first of an electro-optically tunable laser. Thanks to the low-thermal generation and high-speed response of the EO effect, we also achieved less-than-30-mW tuning-power dissipation and sub-nanosecond wavelength switching. The laser also showed a linewidth of less than 350 kHz, which is acceptable for conventional digital coherent systems. We also demonstrated unprecedented high-speed wavelength switching for 128-Gbit/s coherent signals with this laser, which will contribute to the All-Photonics Network.

Keywords: tunable laser, high-speed wavelength switching, electro-optic effect

1. Introduction

A high-speed tunable laser diode (TLD) is key to dynamic allocation of wavelength (λ) resources to individual network units (**Fig. 1**) in our All-Photonics Network (APN) [1]. Since the motivations of this future network are lowering the latency and power consumption of conventional electronic-based network units [2, 3], TLDs are required to be tuned with high-speed and lower power dissipation. Low-noise operation of the laser, i.e., narrow-linewidth performance, is also important to ensure communication capacity by using higher modulation formats with digital coherent technology. In addition to an evolving optical network architecture, TLDs are also beneficial to remote-sensing systems such as those using tunable diode laser absorption spectroscopy [4, 5] and light detection and ranging (LiDAR). For example, the tuning λ-range, tuning speed, and linewidth of a TLD correspond to the beam steering range, scan speed, and detection distance, respectively, in a non-mechanical-type LiDAR system based on coherent detection.

While such high-performance TLDs are indispensable for future optical communication/remote-sensing systems, conventional tuning mechanisms face performance limits (**Table 1**). Laser-chip temperature control (an industry-successful tuning approach [6]) using a thermoelectric controller (TEC) has a poor tuning speed and Watt-class tuning-power dissipation. Although using the thermo-optic (TO) effect with a micro heater [7] is a suitable approach for lowering the tuning power to ~100 mW, the tuning response is limited to a few microseconds, which is not fast enough for the above-mentioned future network systems, which will require a nanosecond-order response in λ-switching. Carrier-injection into a laser cavity [8] is suitable for low tuning power and high-speed tuning; however, linewidth broadening due to the free-carrier-induced noise cannot be avoided.

Therefore, we focused on using the electro-optic (EO) effect as the tuning mechanism of a TLD [9, 10]. The small current generated during EO tuning is beneficial to low-tuning-power dissipation. In

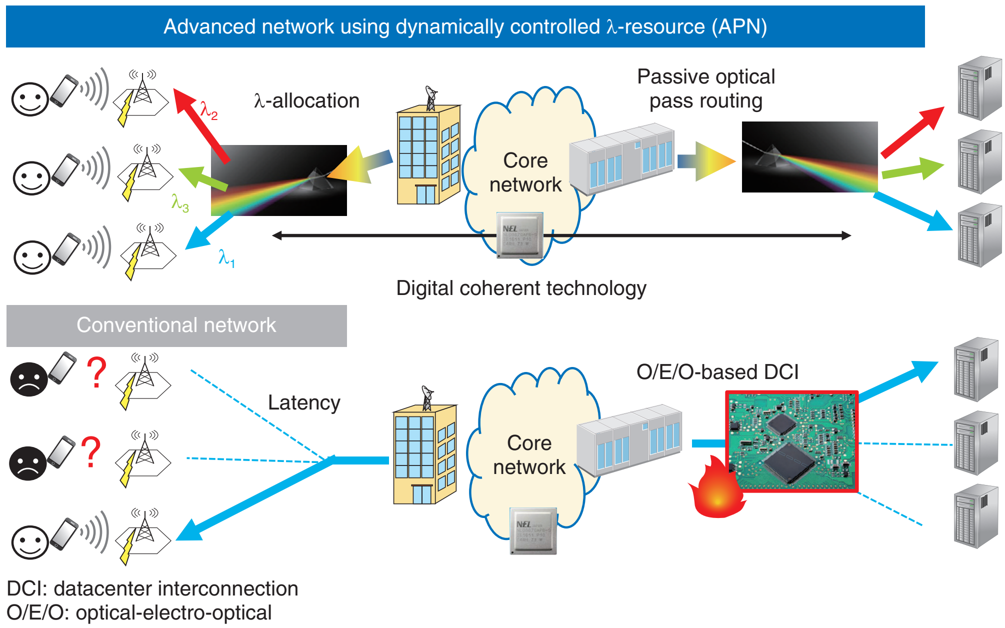


Fig. 1. Advanced network concept based on dynamically controlled wavelength resource.

Table 1. Tuning mechanisms of TLDs.

Tuning mechanism		Tuning response	Tuning-power dissipation	Linewidth	Works
Chip temperature	Optical gain	– >1 ms	– >1000 mW	✓✓ <100 kHz	[6]
Micro heater	Tuning region	✓ <100 μs	✓ 100 mW + α TEC-pow. increase	✓✓ <100 kHz	[7]
Carrier injection		✓ (✓) 10 ns–10 μs thermal drift	✓✓ <100 mW	– >1000 kHz	[8]
EO effect		✓✓ 0.5–50 ns driver limit	✓✓ <50 mW	✓ <350 kHz	This work [9, 10]

addition, the tuning speed is very high since the response depends only on the intrinsic capacitance of the laser cavity, unlike the microsecond-order TO effect using a micro heater. The depletion cavity under a voltage bias used for EO operation is also suitable for narrow-linewidth laser operation, which is difficult for carrier-injection-type TLDs. However, a fatal disadvantage of the EO effect is the small reflective index change (Δn). Even with the quantum-confined Stark effect (QCSE) of a semiconductor multi-quantum well (MQW), which is a type of EO effect with a relatively large Δn compared with other EO effects, the Δn is typically about 10% of the TO and carrier effect. This means that the tuning range of an EO-tunable laser results in an impractical tuning range that is ~10% those of conventional TLDs.

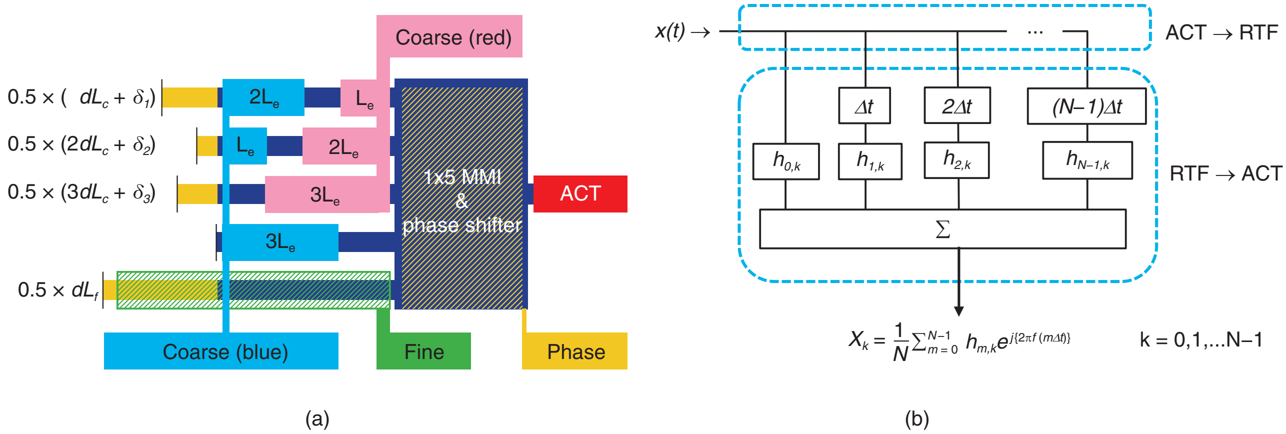


Fig. 2. (a) Schematic of RTF laser and (b) block diagram of general FIR filter.

To use the EO effect for a TLD while overcoming the impractical Δn, we use a reflection-type transversal filter (RTF) [11, 12] as a tunable filter in a TLD cavity. The advantage of an RTF is that we can design the filter tunability (the filter-spectral shift for a given Δn of the waveguide) while tunabilities of conventional filters depend only on the filter-waveguide material. In other words, we can use the EO effect for a TLD with a practical tuning range by compensating for the small Δn of the EO effect with the large tunability of the RTF.

In this article, we discuss the design and present the experimental results of a newly developed EO RTF laser. It exhibits a less-than-30-mW tuning-power dissipation and sub-nanosecond λ-switching with a practical 35-nm tuning range. The laser linewidth is less than 350 kHz, which is acceptable for conventional digital coherent systems. We also discuss the unprecedented high-speed λ-switching for coherent 128-Gbit/s signals with this laser.

2. Design

Figure 2(a) shows a schematic of our RTF laser that consists of an active optical gain (ACT) and RTF for a lasing-wavelength selector. An RTF is an optical-region finite impulse response (FIR) filter, the tap coefficients of which are designed so that the filter has a required spectrum. Namely, signals input into a filter ($x(t)$) are sampled with a time interval, Δt, and each sampled signal is multiplied by a corresponding tap coefficient ($h_{m,k}$). They are then summed with a summation circuit. The system transfer function X_k is shown in **Fig. 2(b)**. We express the *transversal* structure of the FIR shown in Fig. 2(b) with a 1x5 multimode interference coupler (MMI) and reflection-type delay lines. Note that the factor 0.5 of each delay-line length in Fig. 2(a) comes from light making a round-trip in the line. Therefore, this factor vanishes when we consider the corresponding optical path. When signals (broad-band light from the ACT) are input into the RTF, the 1x5 MMI functions as a signal sampler. It also functions as a summation circuit; therefore, the signal (spectrally filtered light) returns to the input port (ACT). When $h_{m,k} = e^{-j\frac{2km\pi}{N}}$, the FIR filter functions as a discrete Fourier transformation (DFT) circuit, and X_k means a DFT coefficient for frequency $f = f_0 + k\Delta f$ (f_0: reference frequency, $N\Delta f = 1/\Delta t$). Therefore, we adopted additional wavelength-order lengths δ_i ($i = 1,2,3$) to express the $h_{m,k}$ in an RTF. In this case, the RTF functions as a DFT circuit, the free spectral range (FSR) of which is $\frac{c}{n_g dL_c}$ in the frequency region. Here, c and n_g, dL_c are the speed of light in a vacuum, a group reflective index of the delay-line waveguide, and unit delay length giving an optical delay of Δt, respectively. As shown in Fig. 2(a), we applied another delay length dL_f to one of the five delay lines rather than a proportional length of dL_c. This produces shorter-interval ripples in the RTF spectrum, which leads to the selection of only one longitudinal mode in the laser cavity. Therefore, while dL_c refers to the DFT spectrum for the *coarse* filter, dL_f is for the *fine* filter. An RTF spectrum calculated with dL_c = ~18 μm and dL_f = ~380 μm is shown in **Fig. 3(a)**.

We define L_e as a unit tuning electro-length and

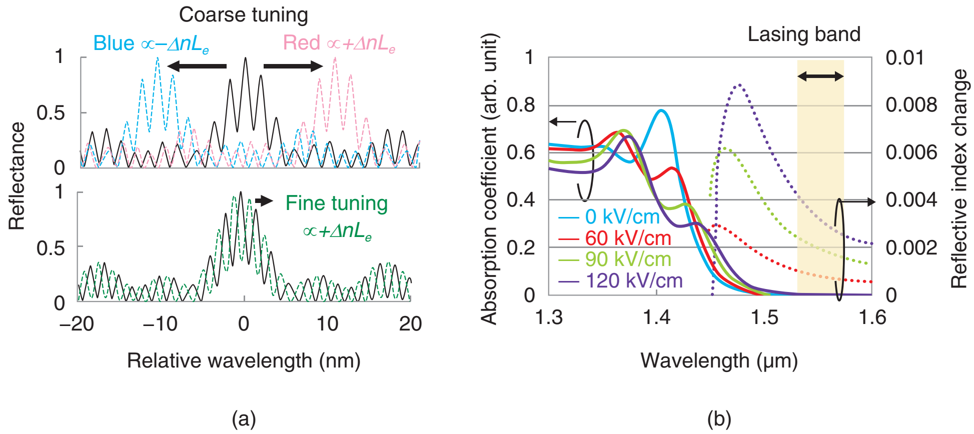


Fig. 3. (a) Calculated RTF spectra and (b) theoretical absorption and Δn change of QCSE.

install electrodes with lengths of iL_e or $(5–i)L_e$ on a delay line with idL_c, as shown in Fig. 2(a). These electrodes are then used for the red and blue shifts of the coarse filter spectrum. The wavelength shift $\Delta\lambda$ is shown as follows [9].

$$\frac{\Delta\lambda}{\lambda_0} = \pm\frac{\Gamma\Delta n(2L_e)}{n_g dL_c}, \qquad (1)$$

where Γ is an optical confinement factor in the MQW of the RTF delay line. We assume $\Gamma = 0.5$ in our waveguide. This relation is introduced by the RTF transfer function. The fine-tuning efficiency is also expressed with a similar expression involving dL_f and L_e [9]. It was found that we can obtain a large tunability when we use a long L_e. The most important advantage of an RTF is that the reflection spectrum is not affected by the shortest delay-line length L_0 shown in Fig. 2(a). Therefore, we can install a long L_e, resulting in large tunability, independently of the filter spectrum. It should be noted that the tunability of a conventional filter, such as a distributed Bragg reflector (DBR), depends only on the Δn (material property).

Since we intend to tune the RTF spectrum with the QCSE, we need to know the Δn to determine L_e. **Figure 3(b)** shows a theoretical Δn derived from the QCSE of our InAlGaAs/InAlAs (indium aluminum gallium arsenide/indium aluminum arsenide) MQW calculated on the basis of $k{\cdot}p$ perturbation theory [4, 13]. It was found that the Δn of our MQW is ~0.003. Using the Δn and Eq. 1, we determined L_e to be 180 µm for $\Delta\lambda = 0.5 \times 35$ nm. The 35 nm is the C-band range and the factor 0.5 in the $\Delta\lambda$ expression comes from the fact that we can use red and blue shifts for the coarse tuning.

3. Laser performance

Figure 4 shows a photograph of our fabricated RTF laser and corresponding schematic of the waveguide structure. The ACT has a ridge waveguide structure and made of an InGaAsP (indium gallium arsenide phosphide) MQW with optical gain in the 1.55-µm-wavelength band. The RTF has a deep-ridge structure and made of an InAlGaAs MQW for the QCSE. After we grow the QCSE MQW on an InP (indium phosphide) wafer, we partially replace the MQW with the active MQW by butt-joint regrowth [14]. After preparing the wafer, we form the ACT and RTF waveguides by dry etching and evaporate electrodes on the RTF and ACT with an electron beam evaporator. While the laser has a deep-ridge structure, we use no resin such as Benzocyclobutene for the planarization in the wafer process to suppress external stress on the waveguide [15].

Figure 5(a) shows the lasing spectra of a fabricated RTF laser. All experimental results shown in this article were obtained with an injection current into an ACT of 40 mA (~6-mW output as shown in **Fig. 5(b)**) and chip temperature of 45°C. We confirmed a 35-nm tuning range (full C-band) for the laser with over 40-dB side mode suppression ratios by applying tuning voltages to four electrodes. The tuning voltages, except for the phase electrode, are as shown in **Fig. 5(c)**. Phase-tuning voltages were also adjusted so that the lasing wavelengths matched the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) grid [16]. We believe that this is the world's first report of an EO-tunable laser with a practical tuning range. Figure 5(c) also

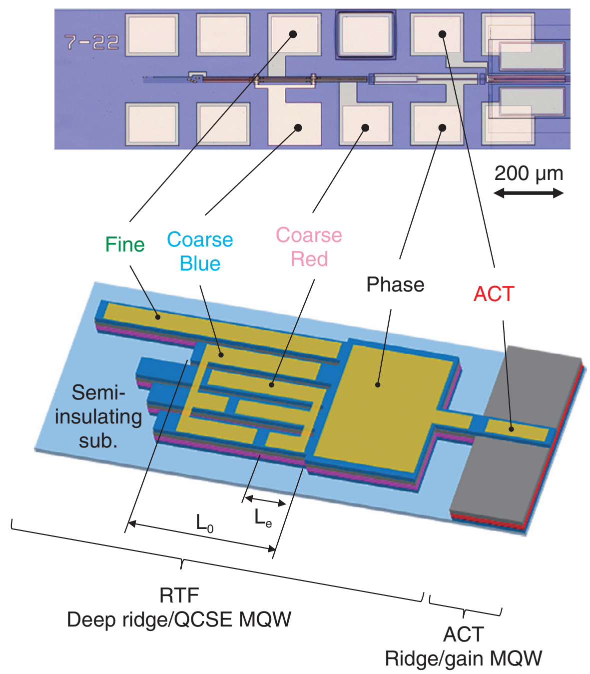


Fig. 4. Photograph of fabricated RTF laser chip and schematic of waveguide structure.

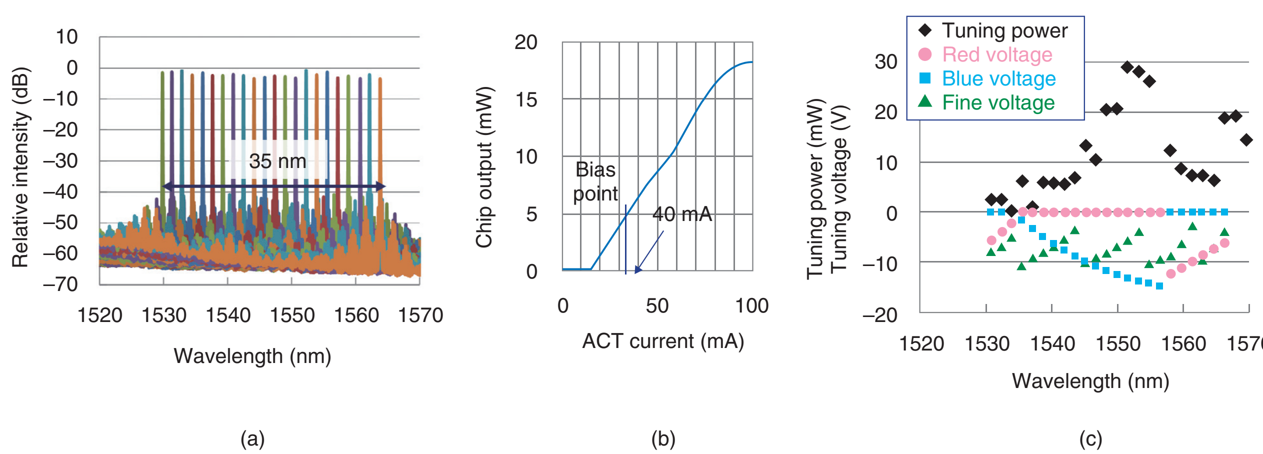


Fig. 5. Basic laser performances of fabricated RTF laser. (a) Lasing spectra with 200-GHz interval. (b) Chip-output power function of ACT current. (c) Tuning voltage and power dissipation.

displays the corresponding tuning-power dissipation defined as the total product of the applied tuning voltages and corresponding photocurrents. We believe that the obtained less-than-30-mW tuning power is remarkably low compared with conventional TLDs. It should be noted that most of the 30 mW comes from the increase in the electrostatic energy of the photocurrents in the depletion layer rather than thermal energy. Therefore, the tuning-power dissipation of the RTF laser hardly increases the chip temperature, resulting in little effect on TEC power dissipation. This is also beneficial in terms of the small λ-drift in λ-switching described below.

In **Fig. 6**, laser linewidths measured using the delayed self-heterodyne (DSH) method are also plotted. We observed linewidths of less than 350 kHz,

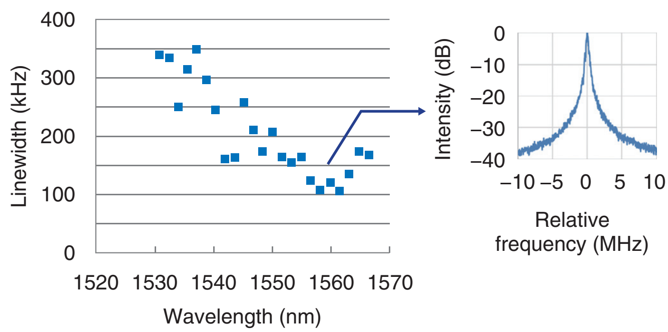
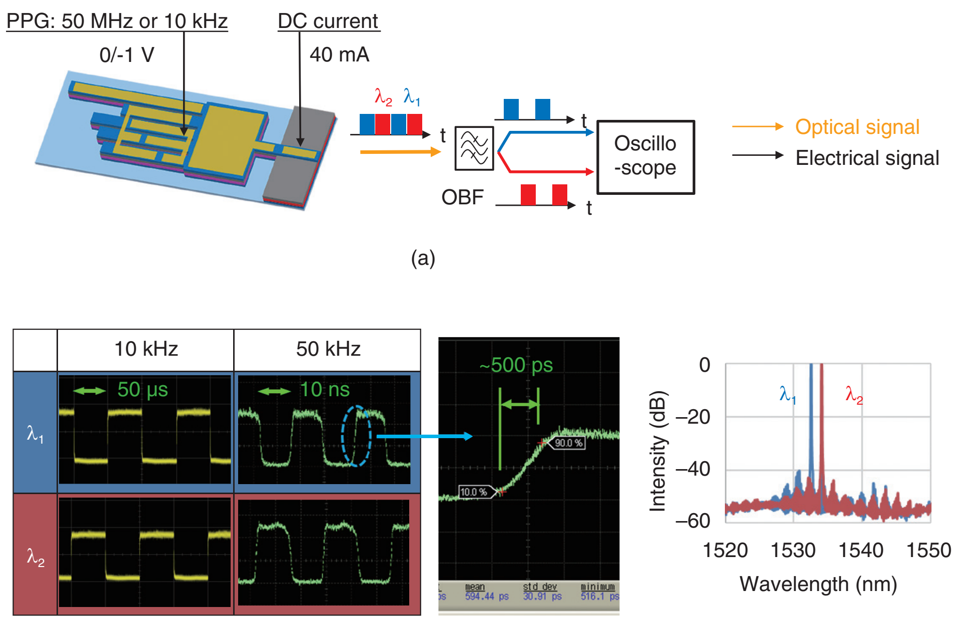


Fig. 6. Laser linewidth and corresponding DSH beat spectrum.



DC: direct current

(b)

Fig. 7. High- and low-speed λ-switching measurement with 50-MHz and 10-kHz square pulses. (a) Experimental setup. (b) Oscilloscope waveforms of detected laser (inset: lasing spectra with switched lasing wavelengths).

which is acceptable for conventional digital coherent technology, indicating the advantage of having a laser-depletion cavity under EO tuning.

We also measured the tuning response of the RTF laser (**Fig. 7**). We applied 50-MHz and 10-kHz square pulses to the RTF laser using a pulse-pattern generator (PPG) and selected a target λ with an optical bandpass filter (OBF). Thanks to the high-speed response of the EO effect, the laser showed a record sub-nanosecond λ-switching time. In addition to the fast response, we confirmed that the response waveforms hardly changed even for 10-kHz modulation. This indicates that there was little λ-drift due to the slow thermal effect during dynamic tuning, which occurs for carrier injection-type TLDs. Although the experiment was rough for evaluating the dynamic wavelength, we also conducted a more detailed measurement using a chirp analyzer and obtained the same conclusion [17]. This dynamically stable performance is practically important to simplify the

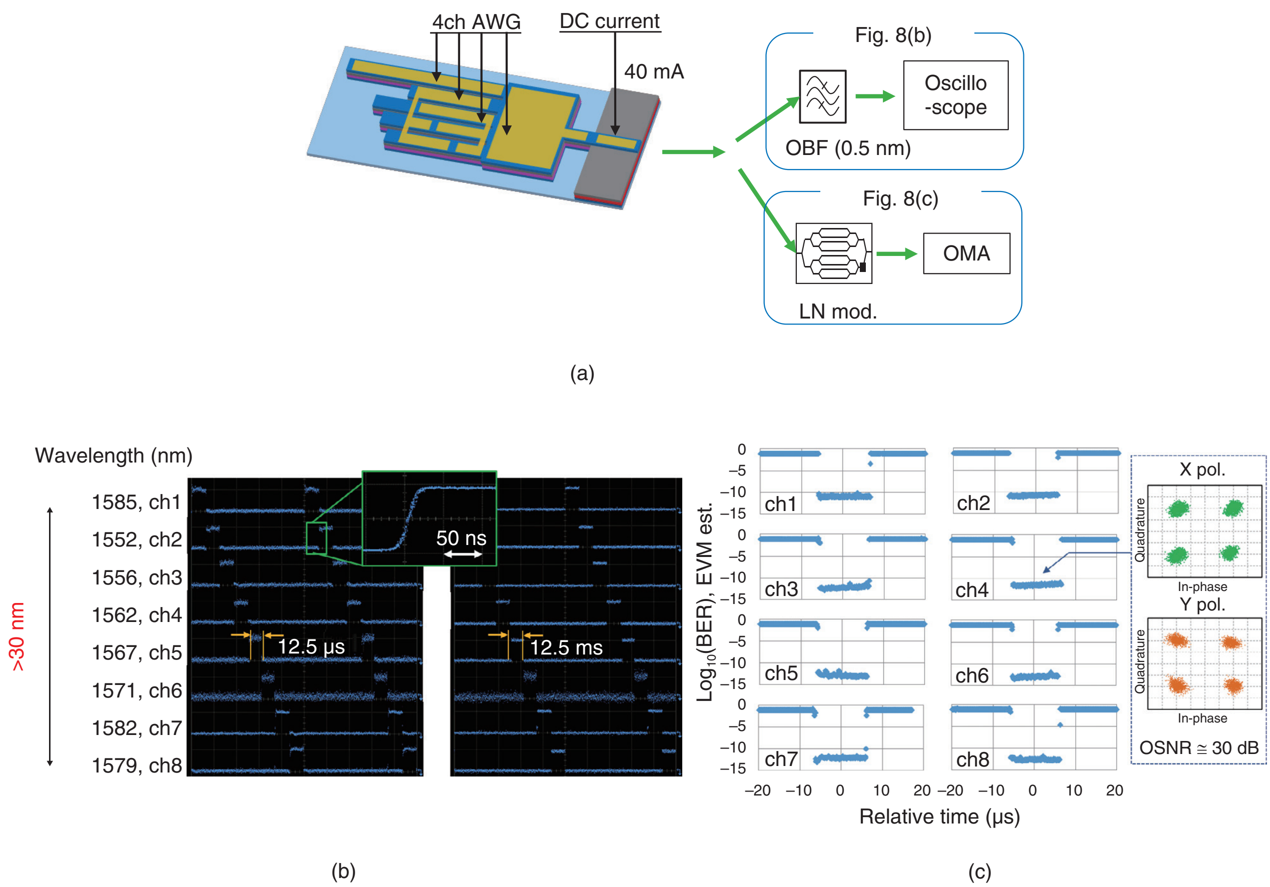


Fig. 8. Eight-channel λ-switching demonstration. (a) Measurement setup. (b) Oscilloscope waveform of detected laser. (c) Dynamic BER and constellation of eight-channel λ-switching for 128-Gbit/s coherent signals. Optical signal-to-noise ratio (OSNR) is set to ~30 dB.

control electronics in optical switching with burst signals described in the next section and in sensing with adaptive tuning speeds, such as for foveated imaging using a swept light source [18].

4. Eight-channel λ-switching for 128-Gbit/s coherent signals

We demonstrated eight-channel λ-switching to prove the feasibility of our RTF laser for optical switching light sources. **Figure 8(a)** shows the experimental setup. We used a four-channel arbitrary waveform generator (AWG) instead of the PPG used in the experiment shown in Fig. 7(a). As shown in **Fig. 8(b)**, we achieved random eight-channel λ-switching with a response time of ~30 ns (AWG bandwidth limit). The important point is that we obtained the same waveform for pulse widths of 12.5 µs and 12.5 ms, which differ by 1000 times. This is a predictable result from the 10-kHz monotonic pulse-modulation experiment shown in Fig. 7(a). This RTF laser is also burst tolerant in addition to having a high-speed tuning response. Finally, we input the λ-switched laser into a commercial lithium niobate (LN) in-phase and quadrature (IQ) modulator. The laser was modulated with 32-GBd dual polarization quadrature phase shift keying via the IQ modulator and detected with an optical modulation analyzer (OMA). As shown in **Fig. 8(c)**, we confirmed dynamic bit error rates (BERs) of less than 10^{-10} in all eight λ-channels, which indicates that the RTF laser has a practically narrow linewidth for a coherent format in addition to high-speed and burst-tolerant characteristics. We believe that the above demonstration results reflect the unique performance of the EO RTF laser.

5. Conclusion

We described the design, basic laser characteristics, and λ-switching demonstration of a newly developed EO RTF laser. The laser has unique characteristics thanks to the excellent EO effect used as the tuning mechanism. We believe that the laser will contribute to future optical networks such as the APN and high-function remote sensing systems using dynamically controlled laser wavelengths.

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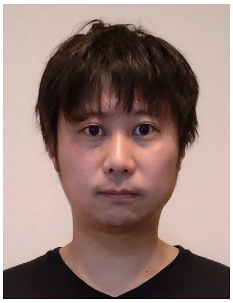

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Standardization Activities Related to Fiber-optic Systems and Active Devices in International Electrotechnical Commission

Shingo Kawai, Kota Shikama, and Makoto Shimokozono

Abstract

The International Electrotechnical Commission (IEC) Technical Committee (TC) 86 is making various international standards for optical-fiber communication. This article gives an overview of the standardization activities of IEC TC 86 and introduces the latest trends and future directions of the recently discussed topics related to fiber-optic systems and active devices.

Keywords: International Electrotechnical Commission, standardization, fiber-optic systems, active devices

1. Introduction

Accelerated by the increased use of the Internet and datacenter interconnections, demand for optical communication systems and related components is increasing dramatically. As new technologies and products diversify, interconnection and quality assurance will become more important in the near future. International standards for interoperability and quality assurance of optical communication systems and related components are actively discussed in the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T), the International Electrotechnical Commission (IEC), and the Institute of Electrical and Electronics Engineers (IEEE). This article gives an overview of the standardization trends of fiber-optic systems and active devices in IEC, which mainly deals with performance standards and test methods.

2. Organizational structure of IEC TC 86

IEC was established in 1906 to set international standards in all technical fields related to electrical and electronic technologies. It makes international standards and provides standard conformity certifications for safety and quality assurance.

Standardization in IEC is carried out in the following hierarchical structure: Standardization Management Board (SMB), which manages and directs standardization activities, Technical Committees (TCs), which are approved by SMB for each technical field and discuss the establishment and revision of international standards, Sub Committees (SCs), which discuss individual technical fields, and Working Groups (WGs), which discuss individual standard documents [1]. As of December 2021, 110 TCs and 102 SCs have been organized.

TC 86 is responsible for fiber optics. As shown in **Fig. 1**, it consists of three SCs: SC 86A, which is mainly responsible for fibers and cables, SC 86B, which is mainly responsible for fiber-optic interconnecting devices and passive components, and SC 86C, which is mainly responsible for fiber-optic systems and active devices. In each field, each WG creates and revises international standards covering terms, characteristics, test methods, calibration and measurement methods, functional interfaces, and

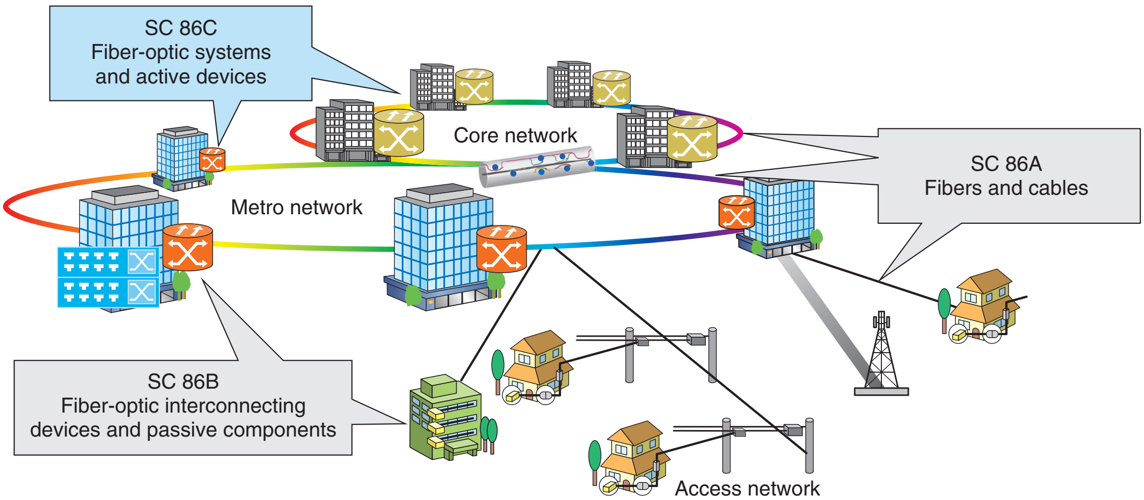

Fig. 1. Technical areas of IEC TC 86.

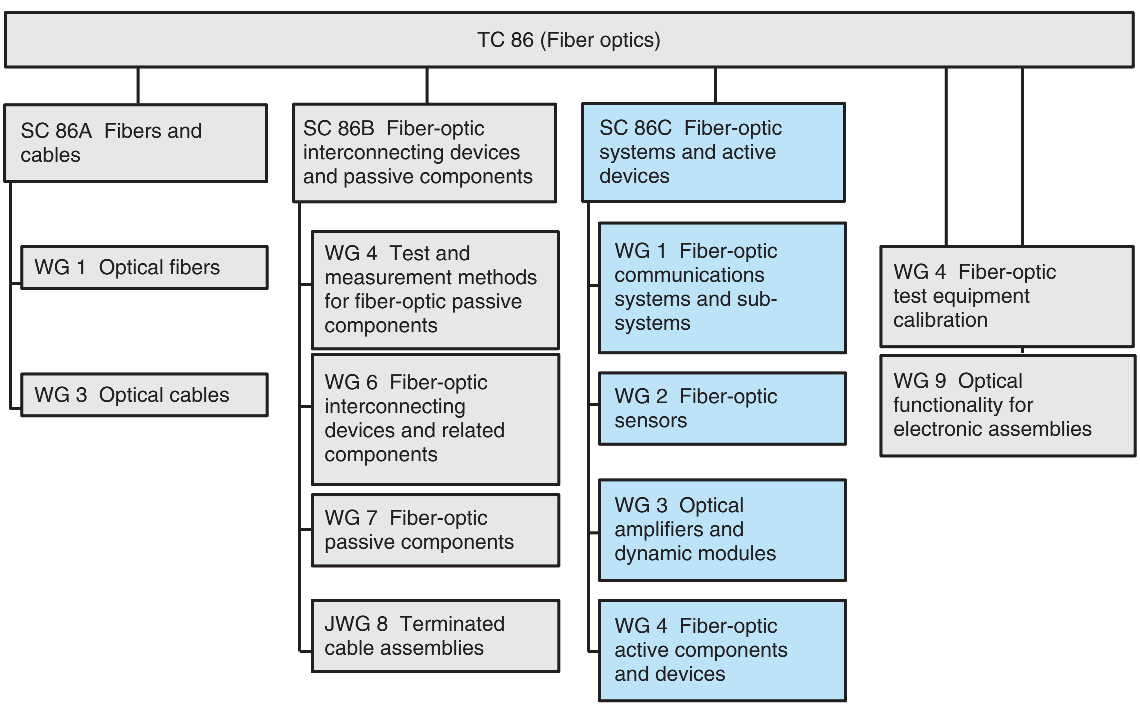

Fig. 2. Organizational structure of IEC TC 86.

optical, environmental, and mechanical requirements. **Figure 2** shows the organizational structure of TC 86. Twelve WGs are organized under the control of three SCs. This article describes the recent standardization trends of fiber-optic systems and active devices discussed in SC 86C.

3. Latest standardization activities of fiber-optic systems and active devices at SC 86C

SC 86C is responsible for the standardization of performance standards and test methods for fiber-optic systems and active devices. In this section, we

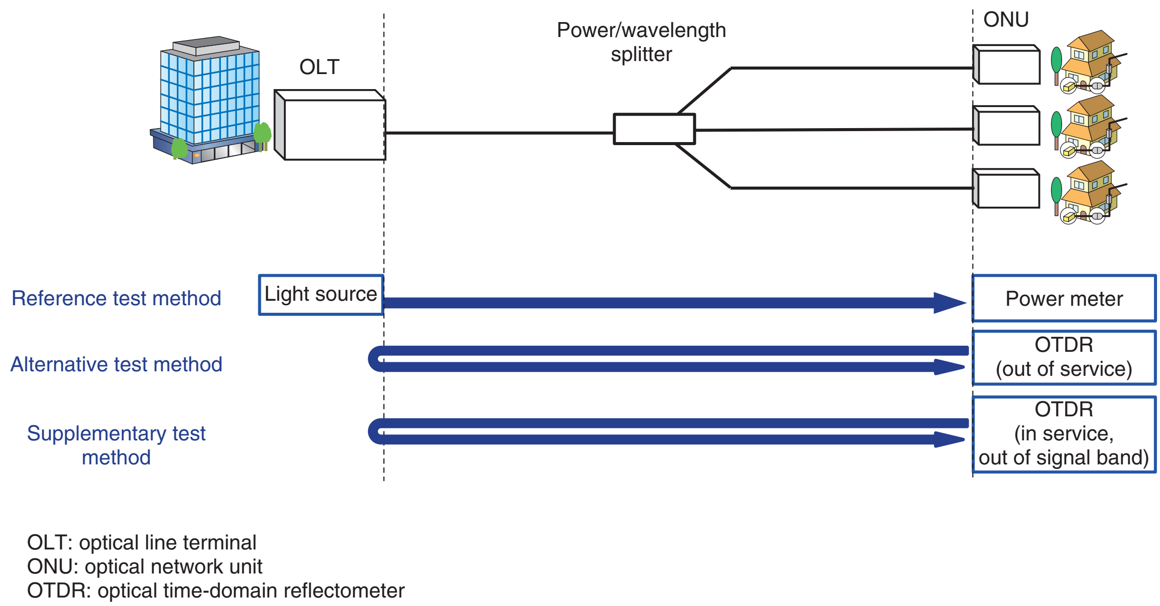

Fig. 3. Loss and return-loss measurement methods for PON systems.

introduce the main topics and their discussion status at each WG.

WG 1 deals with standards related to the physical layer of optical communication systems and subsystems and is proceeding with the standardization of optical-system test methods and design guidelines.

This WG has been promoting the establishment of standards regarding optical subsystems (IEC 61280-4 series), such as loss-measurement methods for existing transmission lines using single-mode fiber and multi-mode fiber cables and for existing cables with MPO (multi-fiber push-on), which is a multi-core connector. It has also established standards for signal-quality measurement methods (IEC 61280-2 series), many of which are proposed from the Japan national committee. Recently, methods for measuring loss and return loss in passive optical network (PON) systems have been actively discussed. **Figure 3** shows the PON system configuration and how to measure loss and return loss. Multiple measurement methods have been proposed, which are basically categorized into two major methods; a method that uses a light source and power meter and a method that uses an optical time-domain reflectometer (OTDR). For the former, how to specify the light source is discussed. For the latter, whether to measure in the upstream or downstream direction and whether to allow in-service measurement are discussed. The Japan national committee is leading the discussion from the viewpoint of reliability of actual network services by giving opinions, such as that the method using a light source and power meter is the reference test method, the method using OTDR is the alternative test method, and the in-service measurement is the supplementary test method and out of standard.

Standards and design guides that focus on digital coherent transmission systems are also under discussion. For instance, error-vector magnitude measurement methods for vector-modulated optical signals in digital coherent transmission systems and design guides for digital coherent transmitters and receivers have been proposed. We are proceeding with these discussions in collaboration with related SCs and ITU-T.

Fiber optics are used not only in optical communication systems but also in non-communication areas, such as sensing. International standards for fiber-optic sensors using optical products are discussed at WG 2. Thus far, standards such as for strain distribution sensors (IEC 61757-1 series), temperature sensors (IEC 61757-2 series), and distributed acoustic sensors (IEC 61757-3 series) using fiber Bragg grating have been discussed, and the Japan national committee is actively expressing opinions and leading the discussions.

WG 3 standardizes product standards and test methods for optical amplifiers and dynamic modules. We have been discussing a wide range of standards

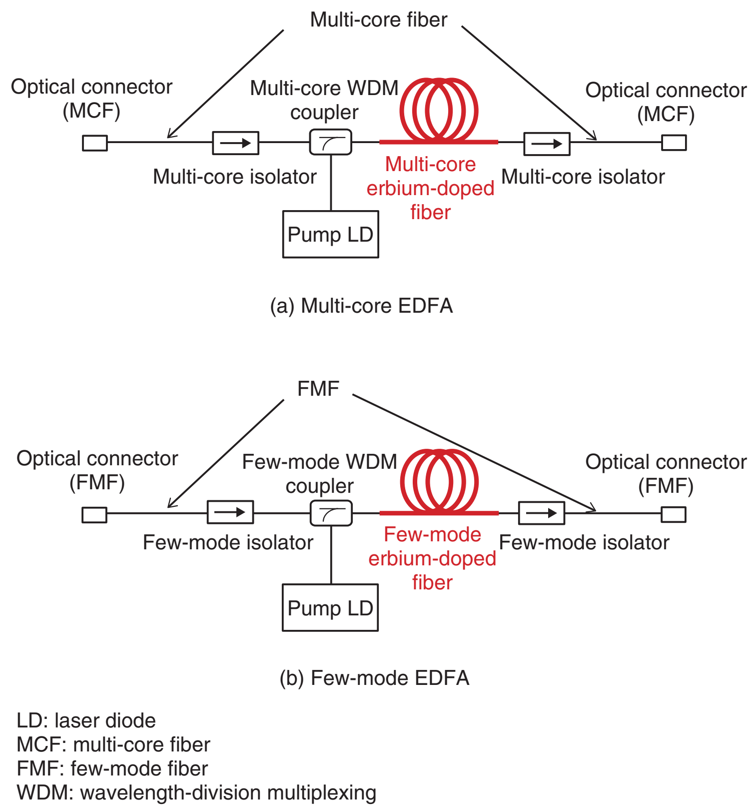

Fig. 4. Configuration examples of space-division-multiplexing optical amplifiers.

such as the definitions of the characteristic parameters of optical amplifiers and dynamic modules, measurement methods, reliability and safety standards, optical-amplifier performance-standard templates, and design guides. The Japan national committee has recently proposed a design guide for space-division-multiplexing optical amplifiers for spatial-multiplexing optical transmission.

Figure 4 shows configuration examples of space-division-multiplexing optical amplifiers. Figure 4(a) shows a configuration example of a multi-core erbium-doped fiber amplifier (EDFA) when a multi-core fiber is used for spatial multiplexing, and Fig. 4(b) shows a configuration example of a few-mode EDFA when a few-mode fiber is used for spatial multiplexing. Various configurations are also being discussed to increase pumping efficiency. Individual core pumping that excites each core, clad pumping that excites all the cores collectively, and their combination are considered for multi-core EDFAs. Individual mode pumping that excites each mode is discussed for few-mode EDFAs. The Japan national committee is leading standardization in spatial-multiplexing optical-transmission technology and will continue to actively propose standards for key technologies.

WG 4 is responsible for the standardization of product standards and test methods for fiber-optic active components and devices. With the technological progress and increasing demand for optical transceivers, the standardization of optical active components using photonic integrated circuits (PICs) has become active. We are in the process of establishing new standards in collaboration with related organizations such as IEEE.

Figure 5 shows an example of a PIC configuration. Since optical and electrical components are integrated on a single board, multiple functions can be mounted at high density, and miniaturization and power saving become possible. To ensure the interoperability and quality of PICs, it is necessary to standardize the size regulation and arrangement of the input/output ports of the electric/optical interface. WG 4 is currently discussing package and interface standards (IEC 62148 series) and performance standards of optical active components (IEC 62149 series). The Japan national committee's activity in

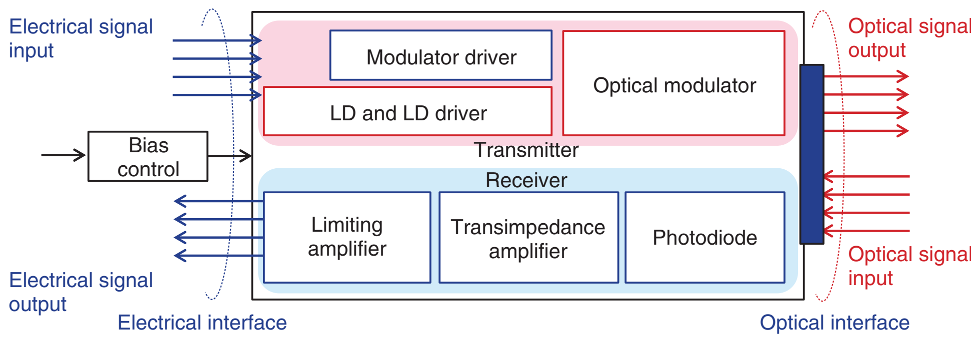

Fig. 5. Example of PIC configuration.

this WG is high and has proposed many standards including interface standards and performance standards for optical transceivers, such as an interface standard that supports high-speed rates of 50/100 Gbit/s.

4. Summary

In this article, we introduced the standardization trends and future directions for fiber-optic systems and active devices in the IEC TC 86 SC 86C. Not limited to the Internet and datacenter interconnection, standardization discussions anticipating markets, such as in-vehicle optical Ethernet for a new application, have begun. There is also active discussion on space-division multiplexing, a future technology that will enable further increase in transmission capacity. While making the best use of the strengths of Japanese science and technology, we will continue discussions in collaboration with other standardization organizations such as ITU-T and IEEE.

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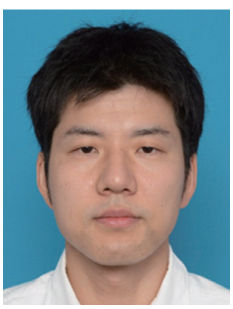

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Development of Loss-evaluation Tool for Efficient Characterization of Optical Fiber Cables

Technical Assistance and Support Center, NTT EAST

Abstract

In conjunction with the spread of the Internet, optical fiber cables have been deployed across Japan to provide a wide variety of Internet protocol services. Since optical fiber cables are installed in various environments, their transmission loss may vary due to stresses such as unintended bending, vibrations caused by passing cars and wind, and aging caused by environmental conditions. Generally, transmission loss in optical fiber cables is evaluated using an optical time domain reflectometer (OTDR); however, to evaluate the condition of optical fiber cables from the data acquired for each fiber, a certain amount of knowledge and experience has been required. Therefore, NTT EAST Technical Assistance and Support Center has been developing a tool that makes it possible to easily evaluate the loss in optical fiber cables from the OTDR measurement data. This article introduces our developed loss-evaluation tool and its functions. This is the sixty-ninth article in a series on telecommunication technologies.

Keywords: optical time domain reflectometer, transmission loss, waveform analysis

1. Introduction

Optical fiber cables enable high-speed, broadband, and high-capacity communications, thus are being deployed across Japan as a social infrastructure not only to support the spread of the Internet and cell phones but also provide new applications using the Internet of Things and artificial intelligence [1]. Since these optical fiber cables are installed both above and below ground in urban and mountainous areas, they are affected by the surrounding environmental conditions such as unintended bending and vibration due to earthquakes and typhoons, and deterioration due to the installation environment. Since these effects often appear as transmission loss in optical fibers, it is important to periodically evaluate such loss as part of cable maintenance [2].

An optical time domain reflectometer (OTDR) is generally used to evaluate transmission loss in optical fiber cables. With OTDR, optical pulses are injected into the optical fiber, and the intensity of Rayleigh backscattered light is measured as a function of round-trip delay time, which is proportional to the distance along the fiber. Accordingly, it is possible to measure the loss distribution as a function of distance along the fiber [3].

2. Evaluation of transmission loss in an actual optical fiber cable

Figure 1 shows an example of transmission loss in an optical fiber cable measured using an OTDR with three different test wavelengths. If an optical fiber cable is deployed in a normal state, its transmission loss increases with a constant slope with distance along the fibers (generally about 0.2 dB/km at wavelength of 1550 nm) [4]. Therefore, the waveform measured using an OTDR (i.e., intensity of Rayleigh

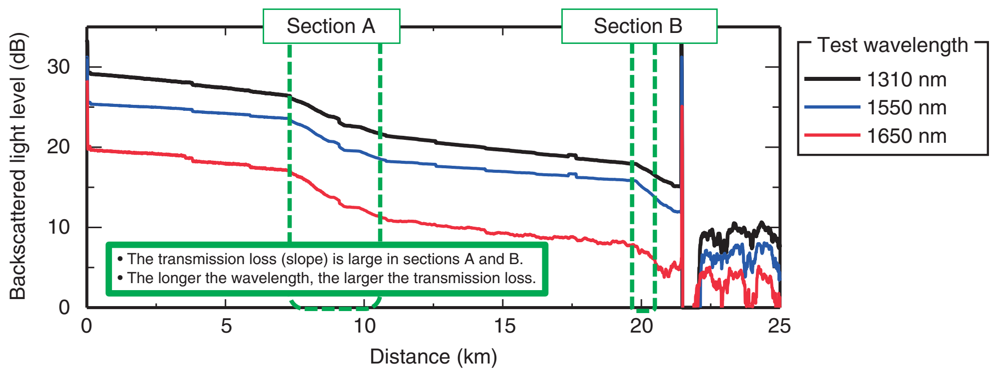


Fig. 1. Example of waveforms measured using an OTDR.

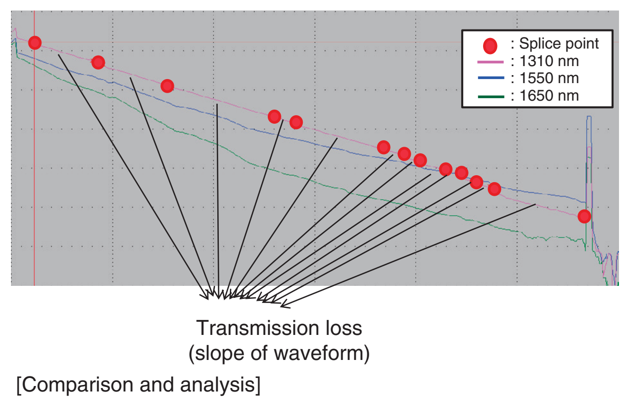
backscattered light) decreases towards the right of the graph. At fiber-splice points, step-like changes in loss (which are associated with the splice conditions) can also be observed.

As shown in Fig. 1, there are steep-slope sections in addition to the step-like loss at the splice points in the OTDR waveform. Comparing the OTDR waveforms among test wavelengths reveals that the slopes of these sections are steeper at the longer wavelength (1650 nm). Because of the wavelength dependence of the loss, it is assumed that stress-induced bending occurs throughout these sections. From the results of previous studies, it is known that such stress tends to increase not only with sudden environmental changes due to disasters but also with cable aging [5].

3. Overview of tool for evaluating transmission loss in optical fiber cables

3.1 Conventional method for evaluating transmission loss

Figure 2 shows the method for evaluating optical fiber transmission loss during conventional maintenance. The evaluator places markers (red lines) on the waveform measured with an OTDR and reads their intensity values to evaluate the change in loss and slope between markers. However, the values often vary according to the evaluator in question, and a certain level of experience and skill is required of the evaluator. Moreover, when a large number of optical fiber cables are measured with multiple wavelengths, the amount of data to be evaluated becomes enormous, and handling such a large amount of data is time-consuming and labor-intensive.



Problem 1	Problem 2
Skills are required for manual analysis.	Huge amount of data to be analyzed. Example: 3 wavelengths × 24 fibers × 38 sections

Fig. 2. Conventional evaluation method.

3.2 Overview of optical fiber cable loss-evaluation tool

Figure 3 shows the optical fiber cable loss-evaluation tool developed by NTT EAST Technical Assistance and Support Center (TASC). The tool has the following four key features:

(1) Batch-reading function for multiple OTDR measurement data
(2) Normal/abnormal judgment based on arbitrarily adjustable analysis conditions (loss threshold, etc.)
(3) Display of a color map of loss per unit length of the optical fiber cable
(4) Display of loss (loss spectrum) for each test wavelength

Each feature is briefly described in the following

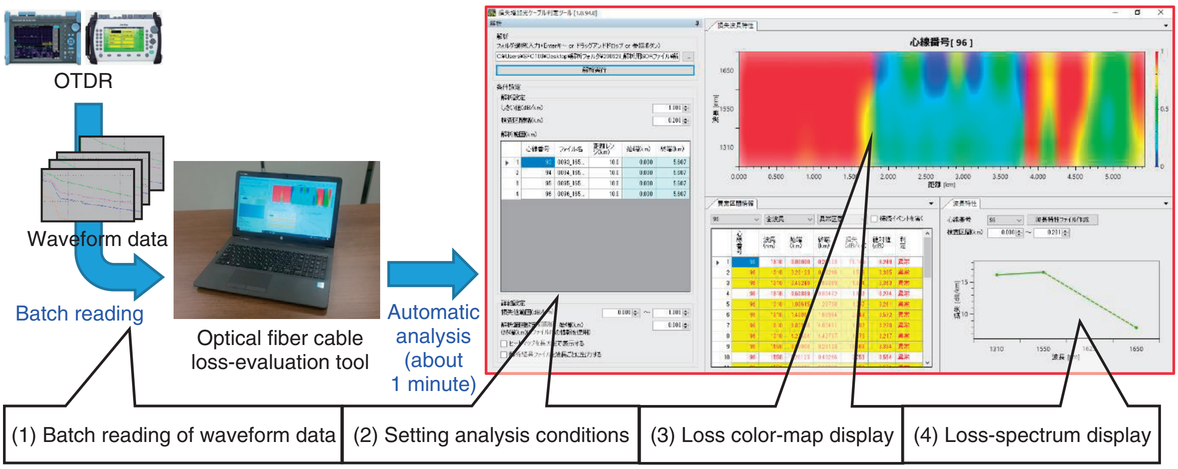


Fig. 3. Features of optical fiber cable loss-evaluation tool.

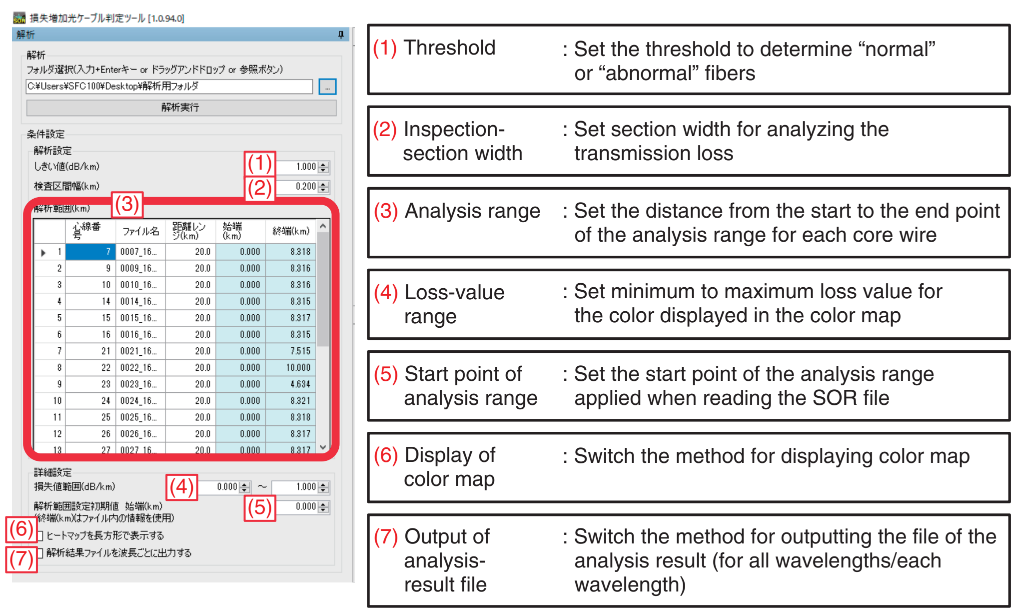


Fig. 4. Example of condition-setting screen.

sub-sections.

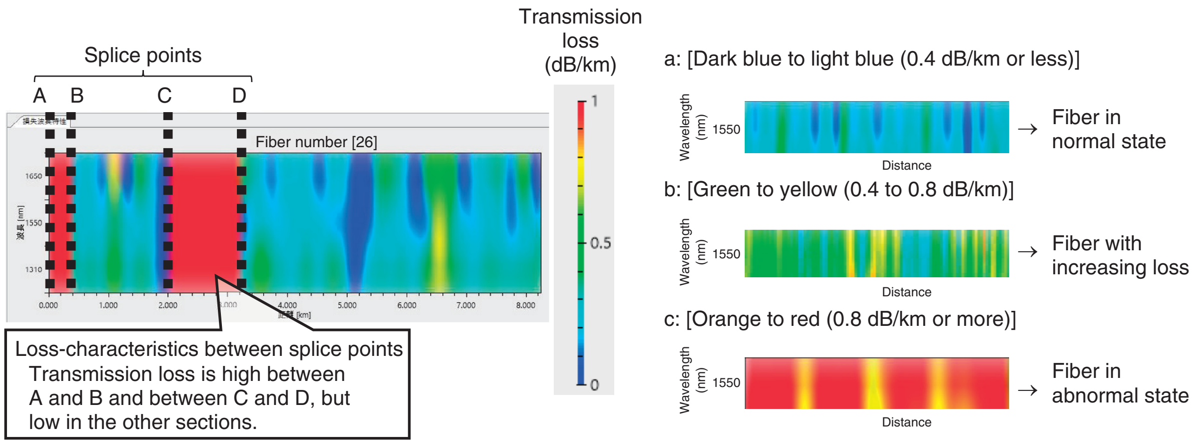
3.2.1 Batch reading of waveform data

To check the loss status of an optical fiber cable, testing at multiple wavelengths is effective. Accordingly, our tool was designed on the basis of multiple OTDR measurement data obtained with three or four wavelengths.

When saving the multiple OTDR measurement data as the file name “(4-digit fiber number)_(wavelengths)_(free text).SOR” (SOR: Standard OTDR Record), the tool can read the multiple measurement data at once and sort them by using the first four digits of the file name as a key and recognizing the wavelength information from the second part of the name.

3.2.2 Setting analysis conditions and normal/abnormal judgment

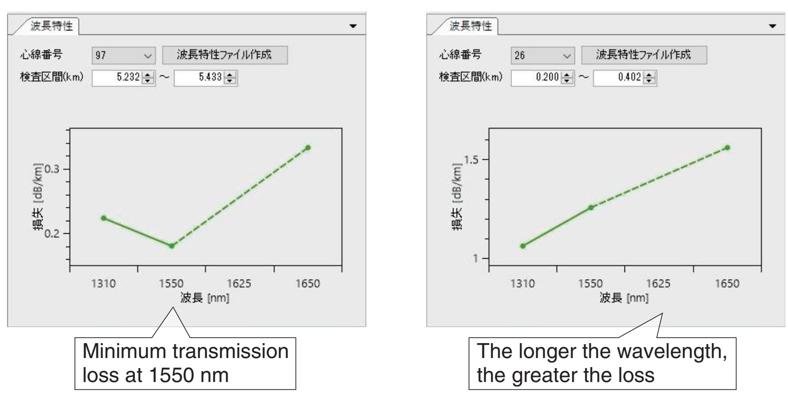
Figure 4 shows an example of the condition-setting screen of the tool. Seven items can be set: (1) threshold, (2) inspection-section width, (3) analysis range, (4) loss-value range, (5) start point of analysis range,



(a) Color-map display

(b) Example of judgment from the color map

Fig. 5. Display of loss distribution by color map.



(a) Example of spectrum in normal state

(b) Example of spectrum in fiber-bending

Fig. 6. Example display of loss spectra.

(6) display of color map, and (7) output of analysis-result file. Arbitrarily adjusting these seven items makes it possible to evaluate losses in accordance with the purpose.

3.2.3 Display of color map of loss distribution

Figure 5 shows a color map of the loss distribution obtained by analyzing the OTDR measurement data.

In Fig. 5(a), the horizontal axis represents the distance along the optical fiber cable, and the vertical axis represents the wavelength. In certain sections, namely, between splice points A and B and between C and D, transmission loss exceeds the threshold.

The change in the color map against the loss value is shown in Fig. 5(b). When the threshold of the slope of the OTDR waveform is set to 1 dB/km, loss values below 0.4 dB/km are indicated in dark blue to light blue. When the loss values are in 0.4 to 0.8 dB/km, the corresponding sections are indicated in yellow-green to yellow. Sections with loss exceeding 0.8 dB/km are indicated in red, so the loss along the length of the optical fiber cable can be checked at a glance.

3.2.4 Display of loss spectra

Figure 6 shows an example of displaying wavelength dependence of loss (loss spectrum) in a certain section of an optical fiber cable. The horizontal axis shows the wavelength of the test light, and the vertical axis shows loss.

For glass optical fibers, loss per distance is lowest at the wavelength of 1550 nm and increases when measured at shorter or longer wavelengths. As shown in Fig. 6(a), analyzing the OTDR measurement data reveals that loss at 1550 nm is minimum for a normal cable. As shown in Fig. 6(b), however, when the optical fiber is subjected to bending, the loss increases with increasing wavelength. Therefore, it is possible to estimate the state in which loss occurs by checking the status of the loss spectrum.

4. Conclusion

We introduced our loss-evaluation tool for efficient characterization of optical fiber cables. Using this tool makes it possible to check at a glance the loss status of optical fiber cables, improving the efficiency of maintenance work. The tool is currently being used by maintenance personnel of NTT EAST and NTT WEST on loan from TASC or used by TASC for analyzing measurement data provided by such maintenance personnel. We plan to further improve the tool so that we can, for example, use the results of periodic tests to analyze changes in loss over time.

At the Access Network Engineering Group, TASC, we provide technical support for solving difficult-to-solve problems of access network equipment that occur in the field across Japan. By applying the skills obtained through technical support and knowledge obtained by investigating the causes of problems, we will continue to contribute to solving such problems and develop tools for improving technical skills and efficiency in the field.

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External Awards

Certificate of Appreciation

Winner: Seishi Takamura, NTT Computer and Data Science Laboratories
Date: December 17, 2021
Organization: Asia-Pacific Signal and Information Processing Association (APSIPA)

For his leadership and dedication to the activities of industrial relations and development of APSIPA as Vice President - Industrial Relations and Development from 2020 to 2021.

Certificate of Appreciation

Winner: Seishi Takamura, NTT Computer and Data Science Laboratories
Date: December 17, 2021
Organization: APSIPA

For serving as an Industrial Forum Co-Chair at the APSIPA Annual Summit and Conference 2021.

Specially Selected Paper

Winners: Sorachi Kato, Osaka University; Tomoki Murakami, NTT Access Network Service Systems Laboratories; Takuya Fujihashi, Takashi Watanabe, Shunsuke Saruwatari, Osaka University
Date: January 15, 2022
Organization: Information Processing Society of Japan

For "CBR-ACE: Counting Human Exercise Using Wi-Fi Beamforming Reports."
Published as: S. Kato, T. Murakami, T. Fujihashi, T. Watanabe, and S. Saruwatari, "CBR-ACE: Counting Human Exercise Using Wi-Fi Beamforming Reports," Journal of Information Processing, Vol. 30, No. 1, pp. 66–74, 2022.

Top Reviewer Award (Top 10%)

Winner: Yoichi Chikahara, NTT Communication Science Laboratories
Date: February 11, 2022
Organization: The 25th International Conference on Artificial Intelligence and Statistics (AISTATS 2022)

Papers Published in Technical Journals and Conference Proceedings

Variational Secure Cloud Quantum Computing

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Physical Review A, Vol. 105, 022603, Feb. 2022.

Variational quantum algorithms (VQAs) have been considered to be useful applications of noisy intermediate-scale quantum (NISQ) devices. Typically, in VQAs, a parametrized ansatz circuit is used to generate a trial wave function, and the parameters are optimized to minimize a cost function. On the other hand, blind quantum computing (BQC) has been studied in order to provide a quantum algorithm with security by using cloud networks. A client with a limited ability to perform quantum operations hopes to have access to a quantum computer of a server, and BQC allows the client to use the server's computer without leakage of the client's information (such as input, running quantum algorithms, and output) to the server. However, BQC is designed for fault-tolerant quantum computing, and this requires many ancillary qubits, which may not be suitable for NISQ devices. Here, we propose an efficient way to implement the NISQ computing with guaranteed security for the client. In our architecture, only $N + 1$ qubits are required, under an assumption that the form of ansätze is known to the server, where N denotes the necessary number of the qubits in the original NISQ algorithms. The client only performs single-qubit measurements on an ancillary qubit sent from the server, and the measurement angles can specify the parameters for the ansätze of the NISQ algorithms. The no-signaling principle guarantees that neither parameters chosen by the client nor the outputs of the algorithm are leaked to the server. This work paves the way for new applications of NISQ devices.

Passive Verification Protocol for Thermal Graph States

K. Akimoto, S. Tsuchiya, R. Yoshii, and Y. Takeuchi

arXiv:2202.10624, Feb. 2022.

Graph states are entangled resource states for universal measurement-based quantum computation. Although matter qubits such as superconducting circuits and trapped ions are promising candidates to generate graph states, it is technologically hard to entangle a large number of them due to several types of noise. Since they must be sufficiently cooled to maintain their quantum properties, thermal noise is one of major ones. In this paper, we show that for any temperature T, the fidelity $\langle G|\rho_T|G\rangle$ between an ideal graph state $|G\rangle$ at zero temperature and a thermal graph state ρ_T, which is a graph state at temperature T, can be efficiently estimated by using only one measurement setting. A remarkable property of our protocol is that it is passive, while existing protocols are active, namely they switch between at least two measurement settings. Since thermal noise is equivalent to an independent phase-flip error, our estimation protocol also works for that error. By generalizing our protocol to hypergraph states, we apply our protocol to the quantum-computational-supremacy demonstration with instantaneous quantum polynomial time circuits. Our results should make the characterization of entangled matter qubits extremely feasible under thermal noise.