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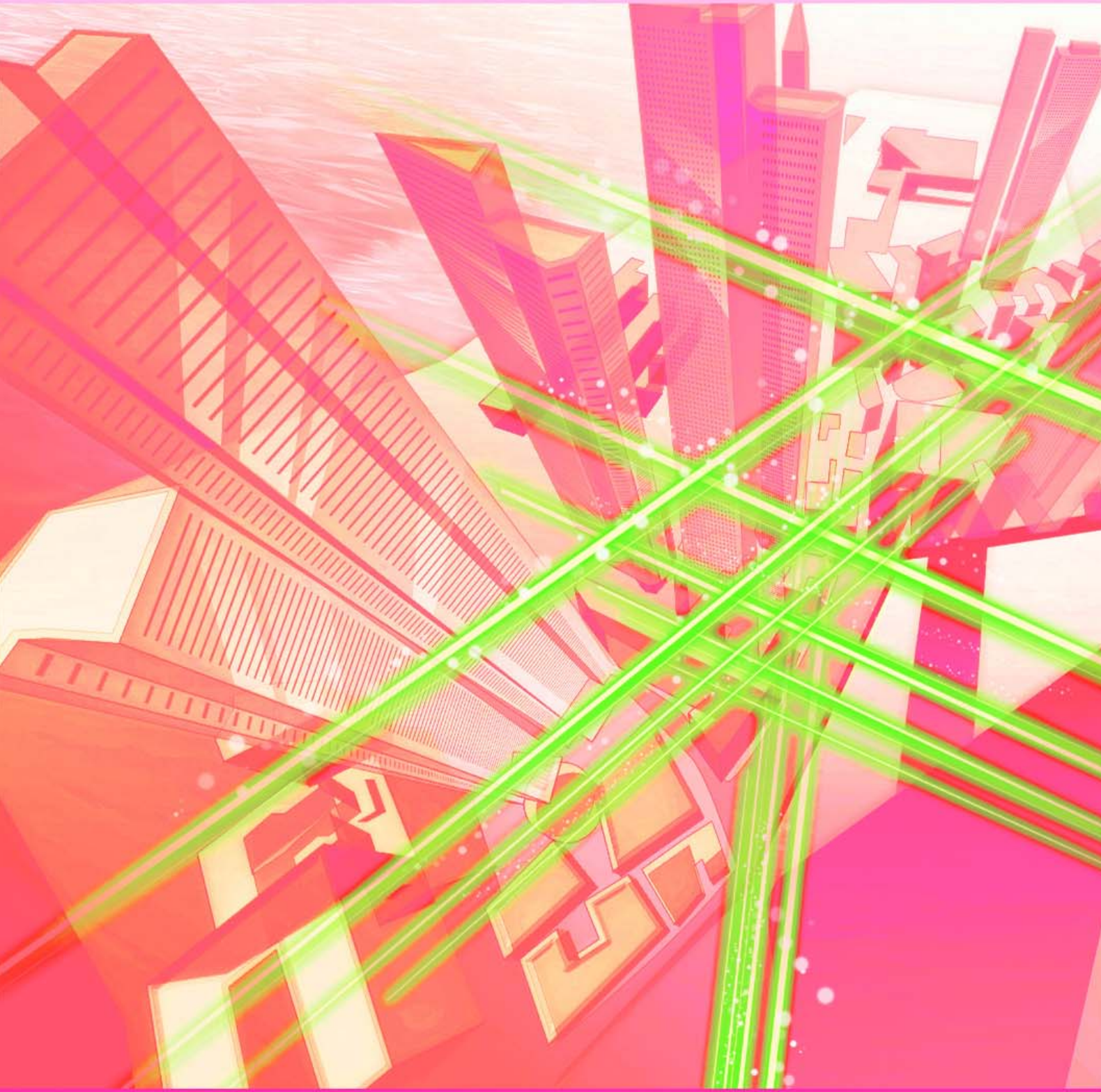

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Let's Change, Challenge, and Implement for Creating a "Wellbeing Society"

Naoki Tani
Executive Vice President, Chief Technology Officer, Executive General Manager of R&D Innovation Division, NTT DOCOMO

Overview

NTT DOCOMO became a wholly owned subsidiary of NTT at the end of 2020. With the launch of 5G (5th-generation mobile communication system) services, its business environment is undergoing a period of major change. Society is also changing due to the novel-coronavirus pandemic, such as acceleration of digital transformation and spread of remote working. We asked Naoki Tani, executive vice president, chief technology officer, executive general manager of R&D Innovation Division of NTT DOCOMO, about the company's efforts to address social issues using technology and how he communicates with employees in this period of change.

Keywords: wellbeing, cyber-physical fusion, Mobile Spatial Statistics

Technology and R&D will lead to creation of a happier future

—First, tell us about the environment surrounding NTT DOCOMO.

We can talk about the environment surrounding NTT DOCOMO from two perspectives: the business environment surrounding NTT DOCOMO and that surrounding the NTT Group. As for the first perspective, in 2020, NTT DOCOMO and other communication companies began providing 5th-generation mobile communication system (5G) services, and the competitive environment changed accordingly. As the second perspective, on December 29, 2020, NTT DOCOMO became a wholly owned subsidiary of NTT.

5G services do not simply provide new technologies to society, they also aim to address social issues and create new value. For this reason, in February 2018, NTT DOCOMO initiated the DOCOMO 5G Open Partner Program, which provides partner companies and organizations (referred as "partners") with information on 5G technologies and specifications as well as a place for exchanging ideas among them. In addition, we established the DOCOMO 5G Open Lab, where partners developing 5G services can test their services with 5G equipment such as 5G radio stations.

In September 2019, we started our 5G pre-commercial services to enable us and partners to create business using the same network equipment and frequency bands as 5G commercial services and enable users to experience the same environment as 5G commercial

services. In March 2020, we launched our fully-fledged 5G commercial services.

Different companies have begun providing 5G services and are promoting 5G's key features, namely, high speed and large capacity. NTT DOCOMO is focusing on solving social issues and creating new value with 5G as well as offering attractive billing plans for users. We have also been leading the international standardization of 5G together with interested parties around the world, and we want to actively promote international standardization beyond 5G, i.e., Beyond 5G and 6G.

NTT DOCOMO has become a wholly owned subsidiary of NTT, so we want to put in place a thorough system so that the research and development (R&D) activities of both companies will be more closely integrated than ever before. NTT DOCOMO is an operating company: we operate in an environment in which customer needs can be directly reflected in R&D and the R&D results can be directly fed back to businesses. Strengthening R&D cooperation between NTT and NTT DOCOMO makes it possible to widen the communication pipeline between the R&D and business departments. In this manner, we want to make the cooperation more coordinated.

I believe that the purpose of NTT DOCOMO is to promote communication between people. To accelerate our R&D, we have set up the "wellbeing society" as a vision for the future, and we are engaged in R&D that will contribute to building a people-friendly society where individual needs can be carefully addressed. In other words, our efforts to address social issues will lead to the creation of a society in which people can live happy, enjoyable lives. Our approach is to build an ecosystem based on three perspectives: industry, society, and individuals. We will develop industries that benefit people, create a social environment in which people can live comfortably, and support people in demonstrating their abilities and live enjoyable and happy lives. I believe that it is our mission to think about what kind of R&D is necessary to meet these goals, and we want to share these goals in our R&D collaboration with NTT.

—Could you give us an example of R&D for creating a "wellbeing society"?

The current focus of our R&D on technologies and services that will create such society is a framework called *cyber-physical fusion*. This framework will also contribute to actualizing the Innovative Optical and Wireless Network (IOWN) being advocated by the NTT Group. People, things, and events in the real world (physical space) are digitized, their data are acquired and accumulated in cyberspace, those data are analyzed to predict the future, and the acquired knowledge is fed back (actuating) to the real world. By repeating the above-mentioned process as a loop, it is possible to create value for people, industries, and societies in the real world, such as providing new experiences, improving efficiency and productivity, facilitating optimization, and ensuring safety and security.

NTT DOCOMO is also taking up the challenge of evolving core technologies to enable cyber-physical fusion. These core technologies include artificial intelligence, which predicts the future and generates knowledge by linking various acquired and accumulated data, Internet of Things (IoT) and device technologies, which provide a means of digitizing the real world and knowledge feedback, and a network that connects the real world and cyberspace. We want to create a "wellbeing society" by evolving these core technologies and establish a platform that can be shared across industries.

As the spread of the novel coronavirus generates restrictions on real-world activities, the shift to the virtual world and online communication is a continuing trend. Following this trend, we hosted "docomo Open House 2021," held from February 4 to 7, 2021, in a completely online format and provided virtual booths that attendees could visit and enjoy the event and exhibitions. For example, we set up a booth where attendees could experience traveling abroad and another in which they could enjoy sports and music with free-viewpoint videos.

Sometimes you may want to see more of or actually see with your own eyes things that you experienced virtually. I think it's important to bring out this feeling by providing a virtual world. The fact that the real world comes after the virtual world means that the greater the value of being able to experience something virtually, the greater the value of it in the real world. I sometimes hear people say that real-world experiences will be replaced with virtual ones, but I beg to differ; there will be more cases in which real social activities are invigorated through virtual ones.

All employees have the potential to unlock the future

—Expectations concerning efforts to improve the real world through the fusion of the real and virtual worlds are rising.

Is the reader aware of the Mobile Spatial Statistics? Among the news about the novel coronavirus, the rate of increase or decrease in the number of people at major train stations has been reported in Japan, and statistical information calculated using our Mobile Spatial Statistics is also used. The Mobile Spatial Statistics is a population statistics service created using the mechanisms of NTT DOCOMO's mobile phone network and provides population-distribution data by gender, age group, and place of residence in real-time minus a minimum of one hour in 10-minute increments [1]. We also provide a service that visualizes

the population of Japan by using high-speed visualization technology developed by NTT laboratories. Using this service, with search/read speed that is seven-times faster than previously possible, users can smoothly display and browse changes in the population of Japan over time. Gender, age, and place of residence in relation to each square (500 m^2) of a mesh covering the whole country can be freely selected and displayed.

As an actual example, a forecast model created in combination with data from a partner is used by store owners to understand the population increase or decrease on a certain day in a particular commercial area. As a result, they can predict sales and adjust the production of lunch boxes and delicatessen items to reduce food loss. Moreover, road-management operators can predict the occurrence of traffic jams on managed roads by determining the population increase or decrease on a certain day in a specific area such as a sightseeing spot. That highly accurate traffic-jam-prediction information is also provided to drivers through smartphone apps, etc., helping to eliminate traffic jams. These cases are examples of embodying cyber-physical fusion and creating services by using the foresight in identifying value in accumulated information, planning ability, and analytical ability.

Although I have talked about services originating from the R&D Department, NTT DOCOMO has a mechanism in which various ideas of employees can be used in new businesses, and the R&D Department supports this mechanism. We will continue to evaluate the possibility of practical application and commercialization of ideas proposed by employees and make them a reality. In this way, I want to value the possibilities possessed by employees other than those directly involved in R&D and services. I believe their possibilities are waiting to be unlocked.

—Can you tell us what you have cherished as a top manager thus far?

The social environment has been changing drastically due to the novel-coronavirus pandemic. I think this change gives us an opportunity to continually come up with new ideas. In such a rapidly changing environment, we should consider three important points: "change," "challenge," and "implement." These may be words you often hear, but I have the following viewpoints.

Let's start with "change." Take a positive mindset that every challenge is an opportunity for change.

"Challenge" is to create a story through your own will. It's important to draw the big picture and act. "Implement" means start quickly with what you can do. It doesn't matter if you "start small." The accumulation of experience little by little will produce outstanding results.

Since many people at NTT DOCOMO are engaged in R&D, the directions of their work may differ. If that is the case, it is important to return to the starting point. During discussions with employees about work or a project, I often ask, "What are we doing this for?" because I sometimes feel that it is necessary to discuss their work from a broader perspective. At such times, I try to improve communication so that we can share the starting point.

It's very important to listen to employees. Rather than telling them to do something, I always want to hear what they think and feel. When I find it difficult to understand what a person is saying, by listening patiently, I can understand his/her true intention. Even if the discussion becomes complicated, responding candidly with "Hold on. What are we doing this for?" will calm the situation and allow us to return to the starting point, share it, and move forward together. Listening to employees also leads to understanding the diversity and discovering the potential of employees.

Return to the starting point to understand the story and purpose

—As your reputation suggests, you seem to be an easy-to-talk-to boss.

Although that may be true, sometimes employees are reluctant to talk to me in my position as their boss, so I try to talk to them as much as possible. Since it is

difficult to take time for each employee, I try to talk to them during meetings. Also, some employees come to see me by spotting gaps between meetings, and I value that kind of time as much as possible. Since we are teleworking these days, I sometimes feel frustrated because I can't communicate with employees easily. Regardless, I still try to have the opportunity to speak to people as much as possible.

As I said above, while listening to everyone, I have viewed everything positively to allow us to "change," "challenge," and "implement." Prioritization is the key to execute these three points. That is to say, select matters so that you can focus on what you think is important. For example, when creating materials, it is important that they are written so that the purpose of the materials can be understood easily. The next important point is where and to whom to talk and how much time to spend. Bosses and customers—as well as external lectures and management meetings—are completely different. What you can convey in 30 seconds differs from what you can convey in one hour. It is very important to devise a way of communicating that firmly corresponds to these different situations. Figures, design, wording, etc. all need to be applied according to the purpose. Therefore, I often ask the person who created such material a question, "What is this used for?" to remind us of the starting point and allow us to understand its story and purpose. I'm always aware of this question, and I want all employees to be aware of it too.

—As a chief technology officer, please give a few words to researchers/engineers.

After joining the company, I worked in the R&D Department of NTT DOCOMO for about 20 years. After working in the Network Department of the Kansai Branch and the IoT Business Department, I returned to the R&D Innovation Division after being away for about nine years. Technology has evolved tremendously over those last nine years.

In the IoT Business Department, where I worked until June 2020, I was working with the aim of creating new business models and increasing profit with partners by using new technologies. During that period, I was observing NTT DOCOMO's R&D from

the outside. After assuming the post of chief technology officer last year, I reaffirmed that NTT DOCOMO possesses many outstanding technologies, and these technologies can be used in our business more than ever.

I encourage our researchers/engineers to take pride in our own technologies and firmly understand the meaning, significance, and position of those technologies. If you keep doing this, you will find opportunities. There are many situations in which the technologies we possess can help solve social issues. If you find an opportunity, you can only take it. I'd like you to keep in mind the three key points I focused on, namely, "change," "challenge," and "implement."

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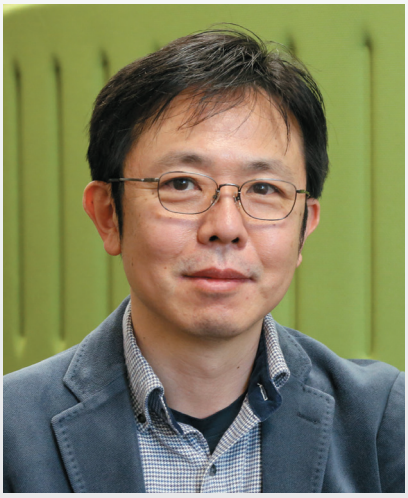
Interviewee profile

■ Career highlights

Naoki Tani joined NTT in 1989 and worked in the R&D Department of NTT DOCOMO from 1992 to 2011. He served as head of the Network Department of Kansai Branch from 2011 to 2014, head of the M2M Business Department from 2014 to 2015, head of the IoT Business Department from 2015 to 2020, and executive officer of NTT DOCOMO from 2017 to 2020. He has been in his current position since June 2020.

Creating a Map of Science and Connecting with the World and Future through It

Koji Muraki
Senior Distinguished Researcher,
NTT Basic Research Laboratories



Abstract

Researchers at the Quantum Solid State Physics Research Group of NTT Basic Research Laboratories focus on the many-body and correlation effects caused by the interaction between electrons as well as on quantum-mechanical properties of electrons such as wave nature, superposition state, and spin. By engineering and controlling these properties of electrons using the heterostructure and nanostructure of semiconductors and atomic-layer materials, the group is investigating quantum devices and sensing techniques that cannot be obtained with individual electrons. Such research is expected to enable the development of ultralow-power-consumption devices and highly sensitive sensors. We asked Koji Muraki, a senior distinguished researcher and leader of this group about the progress of his research and the attitude researchers should have.

Keywords: topological insulator, quasiparticle, semiconductor heterostructure

Quantum correlation brings out the potential of electrons

—Please tell us about your current research.

My research aims to obtain physical properties not found in conventional semiconductors and new functions exploiting such properties by using (i) a structure in which different types of semiconductors are artificially laminated (i.e., *heterostructure*) or (ii) a microfabricated structure (i.e., *nanostructure*). In particular, I'm focusing on the quantum-mechanical properties of electrons, especially a property called *spin*, i.e., having magnetic properties of small magnets, and the *many-body effect*, which is caused by a large number of electrons acting as a group rather than moving around independently.

We are pursuing such research of physical phenomena to engineer and use the properties of electrons that are not used in conventional devices to enable the development of ultralow-power-consumption devices and highly sensitive sensors. Our ultimate goal is to create a quantum computer based on a new operating principle that overcomes the weakness of a conventional quantum computer, i.e., the quantum state changes due to noise (i.e., low error tolerance) (**Fig. 1**).

We are taking two broad approaches to this research. One approach uses the many-body effect

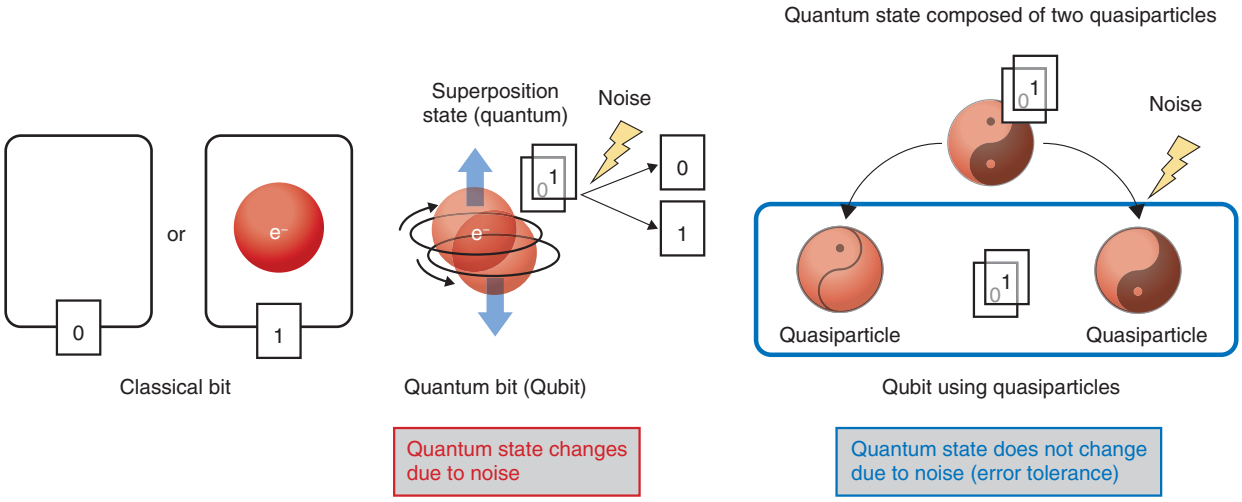


Fig. 1. Quantum bit using quasiparticles.

that I mentioned above, and the other relates to spin and uses a new kind of material called a *topological insulator*.

Before explaining the approach using the many-body effect, I need to explain the so-called *quasiparticle*. For an example of a quasiparticle, let's take a look at a p-type semiconductor, which is a transistor component. If electrons that are negatively charged are missing in the semiconductor's energy levels that they are supposed to fill, those states, called *holes* (because they look like holes from which the electrons have escaped), behave like positively charged particles. Such holes have essentially the same properties as electrons. Our goal is to create quasiparticles with properties that are essentially different from electrons by exploiting the many-body effect.

The other approach is to use a topological insulator. The concept of topological insulator was first proposed in 2005 and is a very new concept in the history of physics. The 2016 Nobel Prize in Physics was awarded to the three physicists who created the theory underlying topological insulators. An insulator is a material that does not conduct electricity. According to the theory proposed in 2005, there are two types of insulators: topological insulators and ordinary insulators, and a layer that conducts electricity always exists at the boundary between the two types of insulators. In 2013, our group experimentally demonstrated that a topological insulator can be formed using a heterostructure of semiconductors [1] (**Fig. 2**). Although various materials have been reported as topological insulators, the topological insulator created using our semiconductor heterostructure can be electrically controlled and switched between a normal insulator and topological insulator by applying a voltage to the gate electrode. In fact, we were the second team in the world to experimentally show that this material system (i.e., the semiconductor heterostructure shown in Fig. 2) can form a topological insulator. The first team published a paper showing that conduction occurs at the edge of the system, and we took time to expand on that paper and showed that the system *is* a topological insulator, that is, it does not conduct electricity excluding the edge of the system. Our paper is still often cited, but being number two made me think about how to present our results.

—You were interviewed eight years ago, and you've achieved numerous results since then.

That interview [2] eight years ago was just after the results of an experiment using a method called nuclear magnetic resonance to show that the spin of electrons under special states are aligned in the same direction due to the many-body effect. The resulting paper was published in Science in 2012 [3]. Since the direction of the spin determines whether the electron can occupy the same position, the paper was highly evaluated as indicating that the electron is in the *special state* predicted by theory. In 2014, using nuclear magnetic resonance once again, we demonstrated that under different conditions, the electrons form a lattice like a crystal and become immobile, and that paper was published in Nature Physics [4]. Although

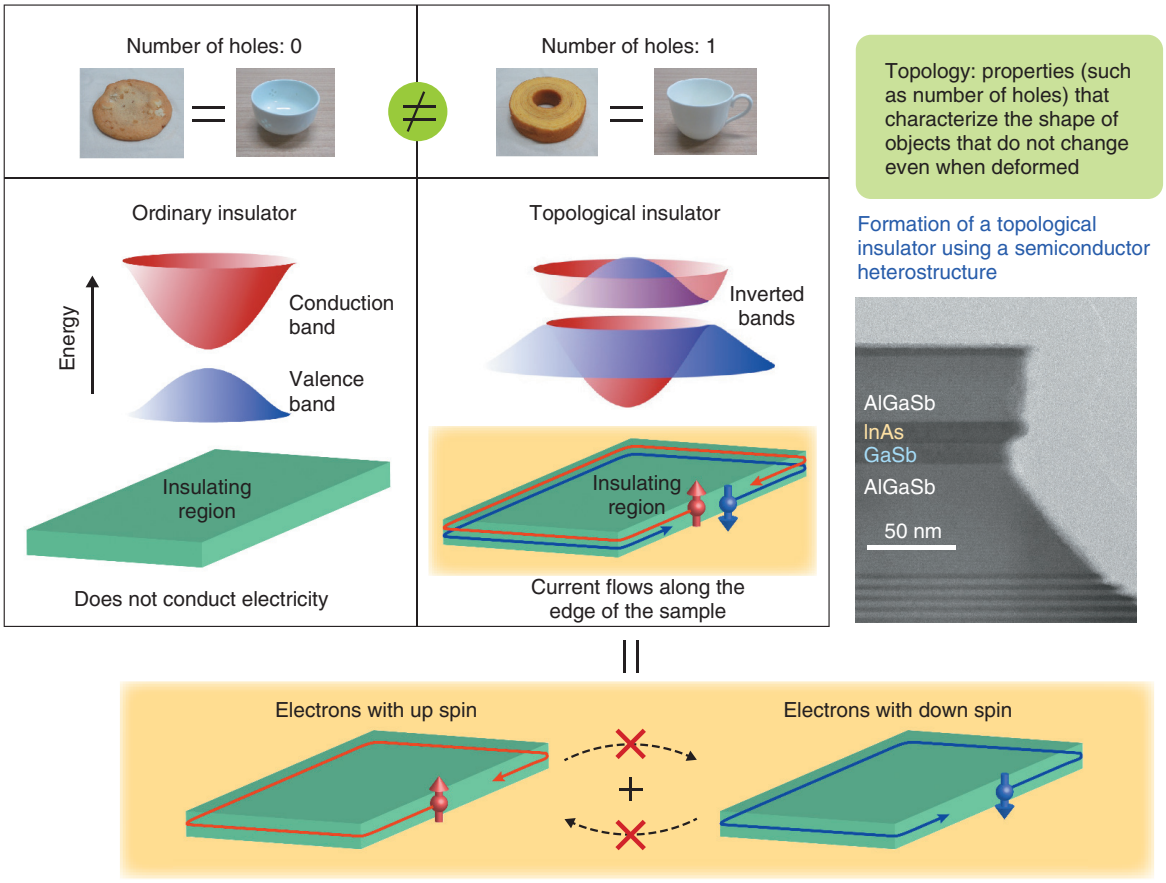


Fig. 2. Formation of a topological insulator using a semiconductor heterostructure.

this paper was published because it was seen as new experimental evidence supporting the long-held phenomenon known as *electron crystallization*, it was not fully satisfactory for us in regard to the original purpose of clarifying the properties of quasiparticles.

Up until that time, I had been investigating the nature of electrons that form the background, or matrix, of quasiparticles; however, more-precise measurement techniques for investigating the properties of quasiparticles have become necessary. Therefore, I invited a researcher at a university to join my group who was interested in the same topic and had the necessary skills and knowledge. Until then, my research style had been to carry out every procedure by myself from sample preparation, measurement, and theoretical analysis; however, I thought I shouldn't keep doing that. For example, the charge on a quasiparticle is smaller than the charge on an electron, and the number of research groups in the world that can measure it is limited. As reported in a recently published paper, by combining nuclear magnetic resonance and quasiparticle-charge measurement, we were able to clarify how the electronic state changes when an electric current is applied. That idea came from a member of my group, not myself.

The next step after forming a topological insulator with a semiconductor heterostructure is to control it electrically; however, this step also faces a problem. That is, an insulator was formed only under very limited conditions, and that limitation was inconvenient

in regard to conducting various experiments. Therefore, by intentionally incorporating materials with the different lattice constant and using the strain in a crystal, in 2016, we were able to improve the properties as the insulator, and in 2020, it became possible to switch between topological insulators and ordinary insulators electrically while maintaining the insulator properties. These accomplishments required a steady accumulation of experiments, such as crystal growth and improvement of the gate insulating film, and those who worked hardest were the young researchers in the group. Although it is now known that various materials are topological insulators, no one has achieved the expected results with regard to the spin properties of the edge of an insulator, and we believe that a real breakthrough will be achieved in the future.

Researchers have no apprenticeship period

—In regard to your research activities, what do you feel has changed since the last interview?

At that time, I was working with a small team consisting of a postdoctoral fellow (a researcher in a limited-term position after obtaining a doctoral degree) and two or three other researchers; however, the number of members involved in the project has now increased. It's my responsibility to coordinate shifts so that young researchers can conduct experiments while taking measures to prevent the spread of the novel coronavirus and support them so that they can devote themselves to research. It is the younger members of the group who are directly involved in challenging experiments.

As a result of the change in my position, I sometimes feel it frustrating that I have less chance to directly engage in experiments. For example, if you're experimenting by yourself, you're the first to see the results; in contrast, when you are working in a group, young researchers conduct the experiment, so they will see the experimental results first. By the time I get to know the research results, a process by which the group members notice something about the results and report it to me had been added. In other words, the results I received had been filtered by other researchers. However, that change is not such a bad thing because other group members can notice things that I might not notice, and the group can achieve results that cannot be achieved with just one person. In consideration of the fact that the members bring proposals and ideas that cannot be thought of by oneself, their contribution is overwhelmingly greater than any amount of my frustration. I feel that I am working in a very blessed environment.

In a position to manage the group, I think it is important to make use of the abilities of individual researchers with multiple interests and specialties so that they can move in the right direction both individually and as a group. Since researchers will not be enthusiastic about a subject they are not interested in, I think it is essential to create an environment in which each member of the team can do what they want to do. For example, even if you can produce results when doing something other than what you want to do, you won't be able to continue producing results in that way. I think unless you feel that you are the one who produced the result or you think nobody else could have produced the result, you won't get a true sense of accomplishment.

What's more, I think that many people who produce results are good at building relationships based on trust with those around them and can collaborate with them. Just because you think about managing a group does not mean that the group will produce good results. However, we are currently able to come up with ideas without hesitation under very good relationships based on trust, so I believe we can continue to produce good results.

—Has there been any change other than research activities during the stay-at-home request period to prevent the spread of novel coronavirus infection?

My passion for the electric guitar, which was my hobby when I was a student, has rekindled. I hadn't played it for a long time, but I revived it while I was staying at home after the state of emergency was declared in April 2020. The electric guitar does not feel right to play unless it makes a loud sound from an amplifier. One reason for my renewed interests is that thanks to digital technology, I can feel as if I'm playing at a loud volume in a concert hall just by generating sound in my headphones. Moreover, many channels on an Internet streaming site host my favorite guitarists explaining how to play, and others allow amateurs to show off their performances. The feeling of being able to connect with people around the world through being interested in the same things is similar to research.

However, research has a special aspect. In the case of music, everyone starts out as an amateur, and only a handful of them become professionals. In contrast, as soon as a researcher becomes a member of a laboratory, they will be treated as a full-fledged researcher

and required to present their research results in papers and at academic conferences. If you have a job in which you also write articles, like a newspaper reporter, I imagine that no matter how many articles you write, they may be turned down by the chief editor and not published in the paper. However, if you are a researcher, you will be required to publish your research results in the form of papers, unless you turn them down yourself. As I said in the last interview, researchers suddenly become professionals without an apprenticeship period or rehearsals.

What I realized this time is the research environment of researchers differs depending on the institution to which they belong, such as companies and universities. For example, researchers at universities will spend more time acquiring research funding than corporate researchers. As a researcher at a company, I realized that I was fortunate to spend less time acquiring research funds than researchers at universities. I thought that that's why I had to discipline myself and put more effort into my research. Sometimes it is important to look at yourself objectively like that and confirm the value of your existence.

I want to achieve results for which it can be said "That was a breakthrough."

—Confirming the value of existence has a philosophical sound. How do you see the work of a researcher, Dr. Muraki?

I think that researchers are self-fulfilling through their research and have the joy of connecting with the world and strangers through research. Through research, we create a map of science and connect with the world and future through that map. If I recall correctly, I also mentioned in my last interview that the work of a basic researcher is to make a *map* and that making a map is an adventure; I haven't changed that way of thinking. Unless your research results were incorrect, you should be able to trust the map you made. Even if the map (research) you are working on is not directly useful, it will be useful in some way. I think that that map can be left to posterity.

However, the way we pursue adventure has changed a lot from eight years ago. Currently, our junior researchers are actually conducting experiments, and I'm in a position to ask questions and give advice based on their results. Although we're going through this adventure together, it's clear that I'm actually less likely to see the results with my own eyes or touch them with my own hands. On the contrary, it is fun to learn from junior researchers, and I'm happy that such opportunities have increased. I want to work with young people doing work for which we can say, "That was a breakthrough."

—Please give a word of advice to the next generation.

When talking to young researchers at academic conferences, it can be overwhelming to find people who are familiar with not only the current state-of-the-art research but also the research done before they were born. I think it's a privilege for young people to be able to study thoroughly what they are interested in. Of course, I'm researching what I'm interested in too, but how much time and energy I can devote to one research topic is far from what young researchers can do.

I think that most young researchers, with a few exceptions, always have a feeling that they can't do what they want to do, don't produce good results, don't seem to be recognized, or feel gloomy. However, those feelings always accompany the privilege of youth, so I want you to concentrate on making the most of that privilege. It would be unworthy of you to worry too much and do not do what you want to do. That is why I want you to broaden your options and cultivate negotiation skills to open up your path.

I recently noticed that there are cases in which younger generations who used to be trainees or postdocs at our laboratories have achieved great results after they had their own research groups and various careers. I think that although their careers as researchers were not plain sailing, the fact that they have diligently accumulated results and built a solid platform over a long period has paid off. Looking at these people, I once again feel that the life of a researcher is pretty long. What they all have in common is an attitude of not giving up.

To live as a researcher, it is important to have the *depth* to delve into what you are interested in and the *width* to observe broader areas. I also want you to take an *exit-oriented* approach striving for the results you aim for in addition to an *entry-oriented* approach focusing on research themes. Many basic researchers may be entry-oriented, but you should continue to dig from not only one side of the *entrance* but also from the *exit* while exploring various possibilities. The idea of digging at various places from *both sides of the tunnel* may be effective in the long run. Therefore, let's listen to the opinions of a wide variety of people to expand our possibilities.

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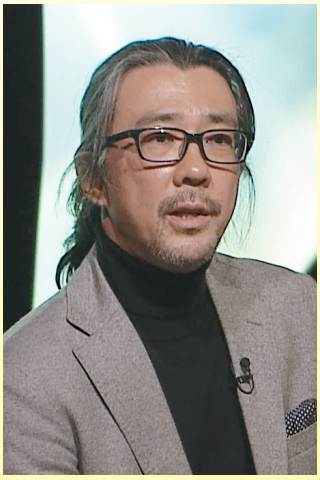
■ **Interviewee profile**

Koji Muraki

Senior Distinguished Researcher and Group Leader of the Quantum Solid State Physics Research Group, NTT Basic Research Laboratories.

He received a B.E., M.E., and Ph.D. in applied physics from the University of Tokyo in 1989, 1991, and 1994. He joined NTT Basic Research Laboratories in 1994. From 2001 to 2002, he was a visiting researcher at the Max Planck Institute for Solid State Research, Stuttgart, Germany. His research interests are focused on the many-body effect in low-dimensional semiconductor structures. He is a member of the Physical Society of Japan and the Japan Society of Applied Physics.

Sports & Live Entertainment Viewing Re-imagined in the Post-coronavirus Era



Shingo Kinoshita

Abstract

On November 19th, 2020, special session 1 of NTT R&D Forum 2020 Connect was held and live streamed. The session welcomed guests Yuki Ota, president of the Japan Fencing Federation and vice president of the International Fencing Federation and Haruyuki Moroishi, CEO and CCO of IMAGICA EEX Inc. and general producer of IMAGICA GROUP. The author, Shingo Kinoshita, executive research engineer, NTT Service Evolution Laboratories, moderated a discussion on the theme "Sports & Live Entertainment Viewing Re-imagined in the Post-corona Era." During the session, they discussed the current status and future of sports and live entertainment during the novel coronavirus pandemic.

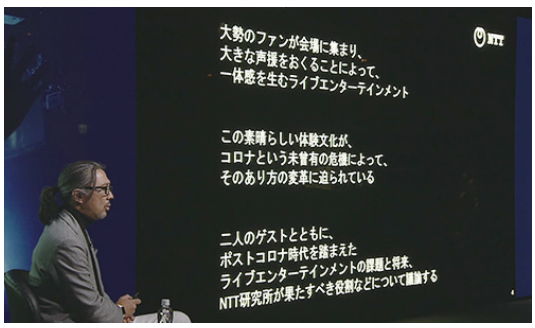
Keywords: sports, live entertainment, experience-oriented

1. Introduction

According to the May 2020 announcement by the PIA Research Institute, the number of live events, including sports, concerts, and theater, canceled or postponed from February 2020 to the end of that year in Japan is estimated to be about 432,000, and the resulting financial loss due to those cancellations is estimated to be 77% of the market size, about 690 billion yen [1]. The amazing experience and culture of sports and live entertainment, through which a multitude of fans gather at a single venue and create a sense of unity by cheering loudly, is being forced to change due to the novel coronavirus pandemic. During special session 1 of NTT R&D Forum 2020 Connect, the participants discussed the challenges and future vision concerning sports and live entertainment in the post-coronavirus era as well as the role that NTT should play.

2. Initiatives by NTT toward the post-coronavirus era

At the beginning, I explained what is happening in the sports- and live-entertainment industries. Many live-entertainment events have been canceled or postponed, and even when an event is held with no spectators or a reduced number of them, cheering loudly and high-fiving are prohibited. Under such



circumstances, online live concerts were successfully held in Japan and abroad by applying creativity and technology. Initiatives were taken to enliven sports venues with no spectators by deploying "virtual fans" via computer graphics and electronic-conferencing systems, and bicycle racing went virtual by using a simulator.

I also introduced a technology called "Kirari!" that NTT has been developing since before the pandemic, which delivers the entire competition space to remote venues in real time by transmission of ultra-realistic information. A demonstration of distributed ultra-realistic viewing, which creates a sense of unity by synchronizing the match venue and remote venues with ultra-low-latency communication technology, was showcased at the session.

3. Initiatives by the Japan Fencing Federation

Guest Yuki Ota, president of the Japan Fencing Federation and vice president of the International Fencing Federation, introduced the efforts both fencing federations have made from before the pandemic to the present. The reform of fencing competitions, which has been ongoing since 2017, was described by Mr. Ota. He talked about how the number of spectators and the unit price of tickets have increased by creating posters to show the coolness of the fencers and changing the venue from conventional gymnasiums to theaters.

He also reported on the remote-watching experience at a finals tournament held with the cooperation of NTT. The "Heartbeat Experience" is a system that allows families of fencers supporting from a separate venue to watch bouts while feeling the heartbeat of the fencers during the bout. Data from a heart-rate monitor worn by a fencer is transmitted to a ball-shaped device possessed by the fencer's family, and the fencer's heartbeat is experienced as "vibration and light." "Remote High Five" is a solution that enables fencers at a tournament venue and their families cheering from another venue to celebrate with high fives. The vibration generated by a person touching a transparent board installed at each venue is measured and transmitted to a remote location together with videos. This solution enables two-way communication even when watching a bout from a remote location in a manner that communicates the excitement and joy of sports.

4. Initiatives by IMAGICA EEX

The other guest, Haruyuki Moroishi, CEO and CCO of IMAGICA EEX Inc. and general producer of IMAGICA GROUP, explained the transformation of the live-entertainment industry's business model during the pandemic. The industry has been growing with the principle of "the supremacy of the real world," but from the perspective of avoiding the "three-Cs" (closed spaces, crowded places, and close-contact settings) and maintaining social distance, this must be changed. He said it seems to being transforming from a "theater-oriented" business model based on earning ticket revenue in the physical space of theaters, etc. to an "experience-value-oriented" business model based on using distribution and live viewing services.

As his latest initiative, he introduced "Tsuyoshi Nagabuchi Online Live ALLE JAPAN," which he was in charge of planning and producing. It was a live performance, watched by more than 100,000 people, of 16 songs delivered online for two and a half hours. By installing three 300-inch light-emitting diode (LED) screens, a 360-degree immersive stage environment was created. On these LED screens, 300 remote audiences were shown, who sang together,

which gave them a sense of unity and real-time experience.

At a normal live venue, there is a spatial distance between the artist and fans due to physical constraints; however, through this new production and expression of communication that uses video and live streaming and application of new technology, the distance of mind between them could be reduced to zero. Mr. Moroishi said that he discovered the possibility of new live entertainment that fuses the real and virtual through this live event.

5. Discussion

While the effectiveness of online live events was being reaffirmed, I asked the guests during the final section of the session about the future of sports and live entertainment. In response, while predicting that future of such events will be a hybrid of online and real events, Mr. Ota expressed a sense of crisis that the oligopoly of a few major event production companies may strengthen as globalization progresses. Mr. Moroishi said that he is looking forward to the creation of new business and the expansion of the entertainment world resulting from the fusion of technology and creativity enabled by the spread of 5G (5th-generation mobile communication system), artificial intelligence, and other new technologies. The discussion was very meaningful and lively on the topic of future sports. Unfortunately, there was not enough time to continue the discussion.

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Shingo Kinoshita
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Challenges of NTT Space Environment and Energy Laboratories in the Coming Space Millennium

Yuji Maeda

Abstract

On November 20th, 2020, special session 2 of NTT R&D Forum 2020 Connect was held and live streamed. The session welcomed novelist Yuya Takashima, the science fiction consultant for "Mobile Suit Gundam THE ORIGIN" and the multitalented entertainer Kaori Manabe as guests. The author, Yuji Maeda, vice president of NTT Space Environment and Energy Laboratories moderated the session on the theme "Challenges of NTT Space Environment and Energy Laboratories in the Coming Space Millennium." Various research challenges tackled by the Laboratories, such as optimal operation technology for fusion reactors, were introduced while referring to the world in which the science-fiction work Gundam is set.

Keywords: space, energy, environmental issue

1. Introduction

NTT Space Environment and Energy Laboratories was newly established as part of the Information Network Laboratory Group in July 2020. Under the basic concept of "Beyond our planet. Beyond our future.", we aim to contribute to the regeneration of the global environment and creation of a sustainable and inclusive society. To this end, we are conducting research to develop next-generation energy technologies, such as nuclear fusion and space solar power systems, technologies that enable resilient environmental adaptation, and technologies to help achieve zero environmental impact.

More specifically, the Laboratories includes the following groups: the Next-Generation Energy Technology Group, which researches overwhelmingly clean energy, such as fusion reactors and space solar power systems, as part of the Zero Environmental Impact Research Project; the Energy Network Technology Group, which researches distribution systems of the generated energy; the Sustainable Systems Group, which researches sustainable systems that reduce emissions of carbon dioxide; the ESG Management Science Technology Group, which scientifically analyzes environmental, social, and governance (ESG) management for predicting the future as part of the Resilient Environmental Adaptation Research Project; and the Proactive Environmental Adaptation Technology Group, which researches physically adapting ourselves to the environment and controlling the climate.

2. "Space Millennium" and the world of Gundam

The first theme of special session 2 of NTT R&D Forum 2020 Connect was "The 'Space Millennium' and the world of Gundam." I asked the question, "Will Gundam 'mobile suit' be necessary for the Earth in the future?" In response, novelist Yuya Takashima, who was involved in the Japanese manga and animation "Mobile Suit Gundam THE ORIGIN" as the science-fiction consultant, cited "mobile workers" as an example. As the predecessor of the "mobile suit," mobile workers, which appeared in "Mobile Suit Gundam THE ORIGIN," are humanoid machines created for lunar development work and can be considered highly advanced versions of a powered suit (also known as powered exoskeleton) currently being developed in the actual world. He said, "I personally think that it would be beneficial if we had something like mobile workers that enable us to move freely in outer space."

Multitalented entertainer Kaori Manabe pointed out the prospect that "If virtual reality technology becomes more advanced, there will be advantages that exceed the five senses." She also said, "Mobile suit is supposed to be worn by humans, however, if communication technology develops, it will be possible for people to not only go into space for real but also, for example, go there by feelings only." I responded, "A world in which robots can be sent alone into outer space and be operated from the Earth is fantastic." and concluded, "We are doing our best to complete our mission to eliminate the world in which communication is not possible, including space communication."

After that, as a problem facing the current global environment, I pointed out that the population of the Earth has already increased too much and is expected to increase further, and asked their opinion about the migration of humans to a "space colony" as a realistic solution. Responding with "I want to go, too!", Mr. Takashima said, "I have an image of staying in a space colony for the long term, which is depicted in Gundam." In response, Ms. Manabe said, "Although we assume that people in a space colony will live the same life as those on Earth, it may be possible, for example, for the body only to exist in the space colony and the mind to live in a virtual world that differs in terms of life and consciousness."

3. The "Space Millennium" and global environmental issues

The second theme was "The Space Millennium and Global Environmental Issues." I started by introducing the challenges NTT Space Environment and Energy Laboratories is undertaking. We are currently researching optimal operation technology for fusion reactors in collaboration with the International Thermonuclear Experimental Reactor (ITER) and the National Institutes for Quantum and Radiological Science and Technology. To extract energy from a fusion reactor, it is necessary to generate a plasma and keep it stable for a long time. Therefore, it is necessary to transfer a huge amount of sensor data from a reactor to the control center, calculate optimum values, and provide instant feedback to the reactor. To implement that process, it is essential to further increase the speed and reduce the latency of the network. Accordingly, NTT wants to contribute to this implementation by using Innovative Optical and Wireless Network (IOWN) technology.

4. Space solar power systems

We are also researching space solar power systems, with which energy generated in geosynchronous orbit is transmitted over 36,000 km to the ground. I think if the laser used for that power transmission is developed, it could also be used to control the weather by warming and cooling clouds and the oceans. We aim to roll out the laser in the real world after carrying out various simulations on the Earth reproduced in cyberspace by using Digital Twin Computing technology and confirming that the laser has no adverse effects on the Earth or people.

5. Concluding remarks

Finally, I asked both guests about what they would

request NTT Space Environment and Energy Laboratories to pursue. Mr. Takashima requested that we conduct research on warp technologies. I replied, "It's a different story when it comes to transporting the human body, but I think warp will be a technology in the field of communications," leaving room for the possibility of the Laboratories entry into research on that topic. Ms. Manabe requested "to continue researching in directions that enrich the natural world by having both the values of a new technology and nature."

Yuji Maeda
Vice President of NTT Space Environment and Energy Laboratories.
He received a Ph.D. in systems information science from Future University Hakodate, Hokkaido, in 2013. He joined NTT Telecommunication Networks Laboratories in 1991. He was engaged in managing projects related to general emergency management such as those concerning natural disaster response and cybersecurity. He received the Scholarship Encouragement Award from the Institute of Electronics, Information and Communication Engineers (IEICE) in 1998. He is a senior member of IEICE and a member of the Institute of Electrical and Electronics Engineers (IEEE).

Toward Cyber-physical Interaction for Natural Connection of Real Space and Cyberspace

Shigekuni Kondo, Atsushi Sagata, Kenichi Minami, and Akihito Akutsu

Abstract

To actualize the concept of IOWN (Innovative Optical and Wireless Network), we need a new "environment" for connecting real space and cyberspace that fundamentally changes our lives without needing to be literate in information and communication technology. Also essential is a natural means of incorporating that environment into our daily lives, which is to say a function for natural cyber-physical interaction. The following Feature Articles in this issue introduce the most recent technological trends concerning cyber-physical interaction at the boundary between real space and cyberspace.

Keywords: perception, body, cybernetics

1. Introduction

In fusing real space and cyberspace by using the Innovative Optical and Wireless Network (IOWN) [1], we can expect more precise simulations that will enable better predictions, thus expanding the range of human activities. In such an environment where there is a fusion of real space and cyberspace and our lives are fundamentally changed, it will be possible for anyone, regardless of their information and communication technology (ICT)-literacy level, to benefit from prediction. To achieve this, we believe it is essential to have natural cyber-physical interaction that involves a natural means of information presentation for fusing our daily activities with the environment.

The Feature Articles in this issue introduce the most recent trends and technologies that concern cyber-physical interaction at the boundary between real space and cyberspace.

2. Overview of R&D on cyber-physical interaction

Research and development (R&D) on the fusion of real space and cyberspace is already progressing to the stage of practical application in many areas, and various types of content have been produced. In computer gaming, for example, game characters are displayed on smartphone screens and superimposed in real space in front of the user, creating the illusion of the characters existing in real space. There are also many games that immerse the user in game worlds. Regarding sports, there are, for example, online bicycle races.

In the future, it will be possible for people to jump into a virtual world (full-dive) and interact with real space through cyberspace. For example, people can share realistic places with others even if no one is actually there or provide realistic support for people who are not at that location, amplifying human knowledge and using human abilities to the maximum extent.

We believe that the user interface will play an even more important role than before in a future where real space and cyberspace are tightly coupled. Technology for information presentation and input in ways that do not interfere with human activities, new interaction technology that uses haptic sensory effects,

technology for making the utmost use of human motor functions, and other such technology are needed for natural integration of people and the environment through natural information presentation, which is to say natural cyber-physical interaction. Cyber-physical interaction expands and develops individual environments by connecting several environments and exchanging well-being and other subjective information as well as objective information, such as efficiency, quality, and cost, between them. A core technology for such interaction provides perception and cognition control.

NTT laboratories will expand R&D on perception and cognition and focus on R&D in the field of cybernetics on the basis of physiology.

3. Current work on cyber-physical interaction

The following Feature Articles in this issue introduce control technology for perception and cognition, which is a core technology for the cyber-physical interaction that is a subject of current R&D by NTT laboratories.

"Improving Depth-map Accuracy by Integrating Depth Estimation with Image Segmentation" [2] introduces a system called HiddenStereo that enables natural three-dimensional (3D) viewing from monocular 2D images. This system is implemented by combining technology for improving the accuracy of depth maps, which represent the distance from the camera to each pixel in the image, and division of the image into regions.

"Affect-perception Control for Enhancing a Sense of Togetherness for Remote Spectators" [3] introduces elemental technology for going beyond simply transmitting and reproducing a sense of presence at an event venue to be experienced by remote viewers. This technology also captures the emotional responses (emotional actions) of the remote audience and creates a feeling of shared togetherness, interaction, and excitement through emotional feedback.

"Visible-light Planar Lightwave Circuit Technology and Integrated Laser-light-source Module for Smart Glasses" [4] introduces an ultra-compact RGB (red, green blue) laser-light-source module sized to fit into the temples of smart glasses. The module is implemented with an optical system that bundles light sources that produce the three primary colors of light (RGB) with a circuit that is drastically reduced in size.

"Fine-grained Hand-posture Recognition for Natural User-interface Technologies" [5] introduces research for establishing finger-shape recognition technology to implement operation of smart glasses through hand gestures.

"Information-display Method for Reducing Annoyance by Gaze Guidance" [6] introduces an information-display method that both reduces the user's feeling of annoyance and increases the certainty of information access by using an imposed display technique that gives the user the feeling that the act of reading information was their own choice.

"Presenting Material Properties with Mid-air Pseudo-haptics" [7] introduces a mid-air pseudo-haptic technology that gives the user the perception of the material properties of virtual objects as the user manipulates them through their own action.

"Evaluation of Adaptability to Unfamiliar Environments Using Virtual Reality" [8] introduces research on creating technology for evaluating and improving the ability to adapt to the environment to achieve appropriate exercise and prevent accidents involving the elderly while walking or driving.

4. Conclusion

We described the R&D on technology for cyber-physical interaction at the boundary between real space and cyberspace, particularly the most recent research on perception and cognitive control. We are also investigating other core technologies for cyber-physical interaction, including technology for physiological control, emotion and desire control, communication of the five basic and other human senses, communication control, and social capital infrastructure.

Toward making IOWN a reality, NTT laboratories have been working to bring on-going work related to perception and cognition to maturity and will continue to promote R&D on cyber-physical interaction as an unprecedented user interface based on human proprioception for a seamless connection of bodies in cyberspace and those in real space in the field of cybernetics.

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Improving Depth-map Accuracy by Integrating Depth Estimation with Image Segmentation

Masato Ono, Yumi Kikuchi, Takashi Sano, and Shinji Fukatsu

Abstract

NTT Service Evolution Laboratories is conducting research and development on new media-processing technologies to enable natural interaction by presenting information that influences the visual senses. This article introduces our current research and development of a media-processing technology for improving the accuracy of depth maps by combining depth estimation with image segmentation and a system that uses this technology to generate HiddenStereo (a technology developed by NTT Communication Science Laboratories) images, which enables natural three-dimensional viewing from monocular two-dimensional images.

Keywords: 3D images, video streaming, depth maps

1. Integrating depth estimation with image segmentation to improve depth-map accuracy

Depth maps are a representation of the distance from the camera to the subject for each pixel in an image. They have various applications, including the familiar smartphone camera function that blurs distant background images when taking a picture and detecting nearby objects for self-driving vehicles.

We are conducting research and development (R&D) on a media-processing technology for improving the accuracy of depth maps by converting two-dimensional (2D) content into 3D content in addition to effectively representing newly created 3D content in the entertainment field (**Fig. 1**). This technology is composed of depth-map-generation technology, which generates accurate depth information from 2D images, and depth-map-optimization technology, which corrects depth maps for effective 3D representation and other purposes.

2. Technical points

(1) Depth-map-generation technology

There are various methods for obtaining depth maps, such as using the parallax between images from stereo cameras, combining camera images with information from a separate device (LiDAR*, etc.), or using various image-processing techniques. Deep learning has also been used recently to generate depth maps from 2D content, but the depth maps are generally of low resolution, and depth maps with clear outlines of the subjects cannot be obtained. When applied to recent high-definition (4K/8K) images, the resolution and quality of a depth map must also be high.

Regarding edge-preserving smoothing [1, 2], we are developing a technology for correcting depth maps, improving their accuracy, and enabling effective 3D representation by defining clear outlines for each subject in an image and performing edge-preserving smoothing on the results of image segmentation

* LiDAR: light detection and ranging.

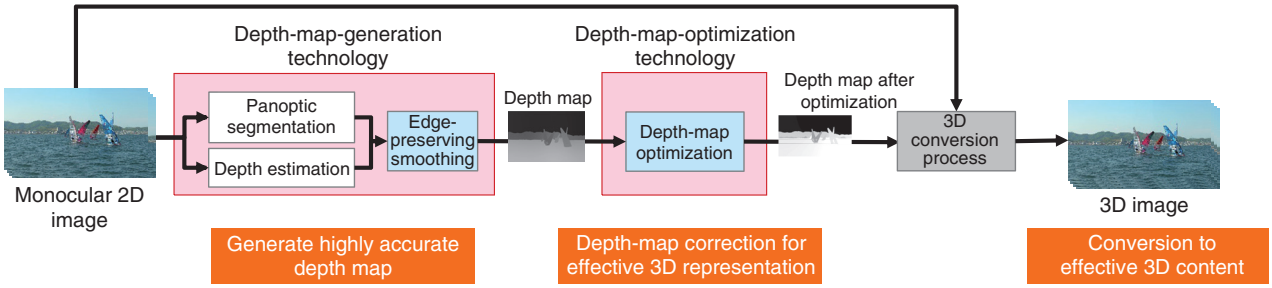

Fig. 1. R&D of media-processing technology for improving the accuracy of depth maps.

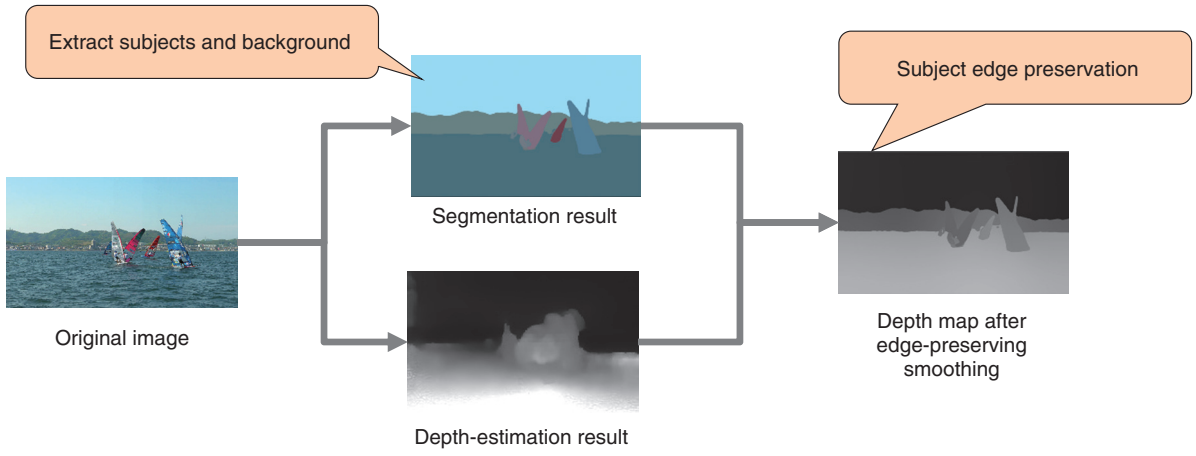

Fig. 2. Depth-map-generation technology.

(**Fig. 2**). Specifically, the resolution of a depth map can be increased by filtering the low-resolution depth map obtained though depth estimation using the segmentation-result image as a guide, while also preserving the edges of the subjects in the image. We use the results of *panoptic segmentation*, which is a combination of semantic segmentation and instance segmentation, to enable separation of subjects and the background.

With this technology, depth estimation and segmentation are only loosely related, so the algorithms for each can be adjusted as necessary. For example, we are currently using deep-learning algorithms for both depth estimation and segmentation, but other algorithms, such as those including self-supervised learning, can easily be substituted.

(2) Depth-map-optimization technology

The depth-map-generation technology described above can provide accurate depth maps, but when used as is, the maps may not necessarily be suitable for a particular application. For example, if the depth in the image is simply reduced to the depth range that can be expressed as a depth map, the depth difference in the image will not be sharp and the 3D expression will not be effective.

As a consequence, methods are used to correct depth maps to improve the sense of presence when viewing the 3D video. We are also developing a technology for optimizing depth maps, emphasizing the sense of depth surrounding the subject(s) that are the focus, to achieve a more effective 3D effect (**Fig. 3**). In particular, corrections are made from the following two perspectives.

(a) Limiting the range of depths used in 3D representations

A perceptual tendency when viewing in 3D is that it is difficult to distinguish fine depth differences in areas that are distant in the depth direction from the subject of focus (i.e., far in the background or close in the front), so we reduce the range of depth differences

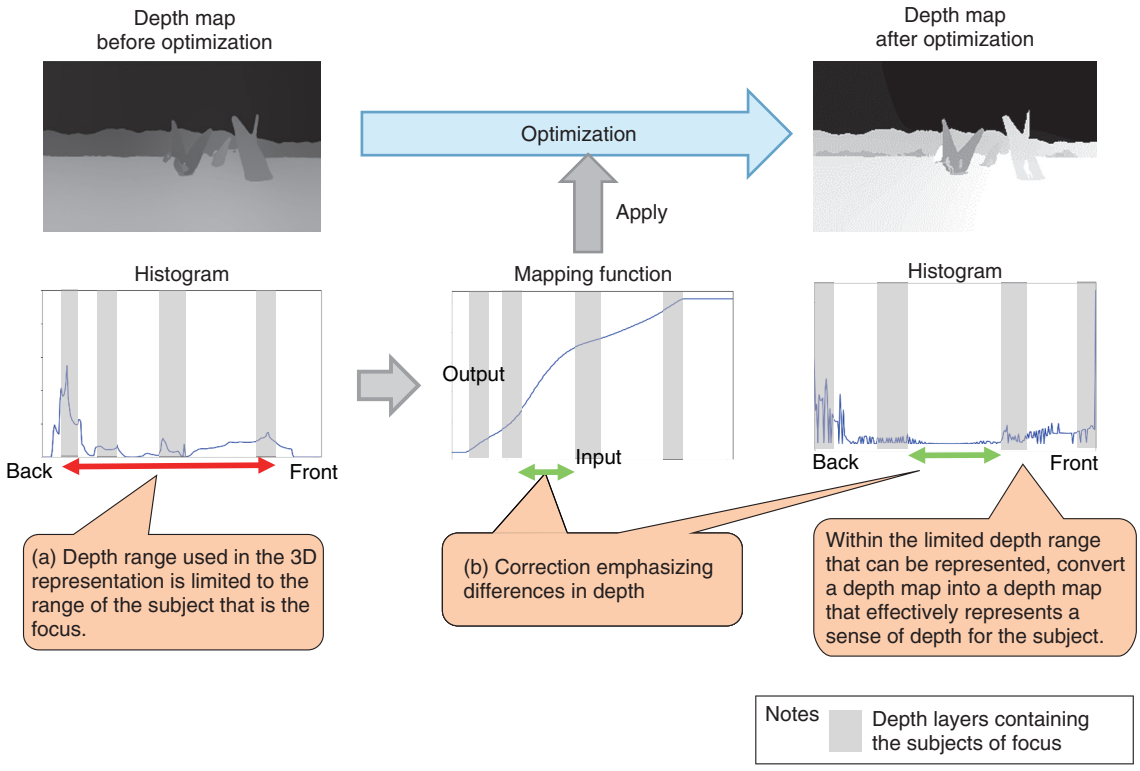

Fig. 3. Depth-map-optimization technology.

allocated to those depth ranges. Specifically, we analyze a depth map represented in steps from 0 to 255, create a histogram, and define ranges containing the subject as *effective depth ranges*. For example, this could be the range from the 5th percentile to the 95th percentile in the distribution of depth values from the depth map. Depths within this range are then extended over the range from 0 to 255, and values outside this range are mapped to either 0 (farthest) or 255 (nearest). Therefore, the 3D representation only expresses the effective depth range for 3D viewing.

(b) Representations emphasizing depth differences

By emphasizing the sense of depth in the range near the subject of focus, 3D video representing more subtleties can be generated. Specifically, from the depth-map histogram, we derive depth layers from the depth ranges containing the subjects of focus. The range of the depth layer with the subject to be emphasized most is then expanded, and the positions and depths of each of the depth layers are adjusted to emphasize the depth representation of that layer. This generates a mapping function for depth values, with input depth values on the horizontal axis and output values on the vertical axis, which has a segment for each depth layer. The segment for the layer containing the most emphasized subject has the greatest slope.

On the basis on the above two points, we derive a mapping function (nonlinear depth-map transform) to correct the depth map and apply it to the depth-map image, generating an optimized depth-map image.

There are various types of 2D archive video containing a range of camera work and scene changes, so the content of depth maps tends to change greatly with time. To enable depth-map optimization that can produce effective 3D representations for all such cases, we intend to continue applying our depth-map-optimization technology to various types of content, evaluate the results, and improve the quality of depth-map optimization.

3. Use in HiddenStereo

We are currently promoting the development of a system to generate HiddenStereo (a technology developed by NTT Communication Science Laboratories [3]) images, which enables natural 3D viewing using depth maps generated and optimized using all

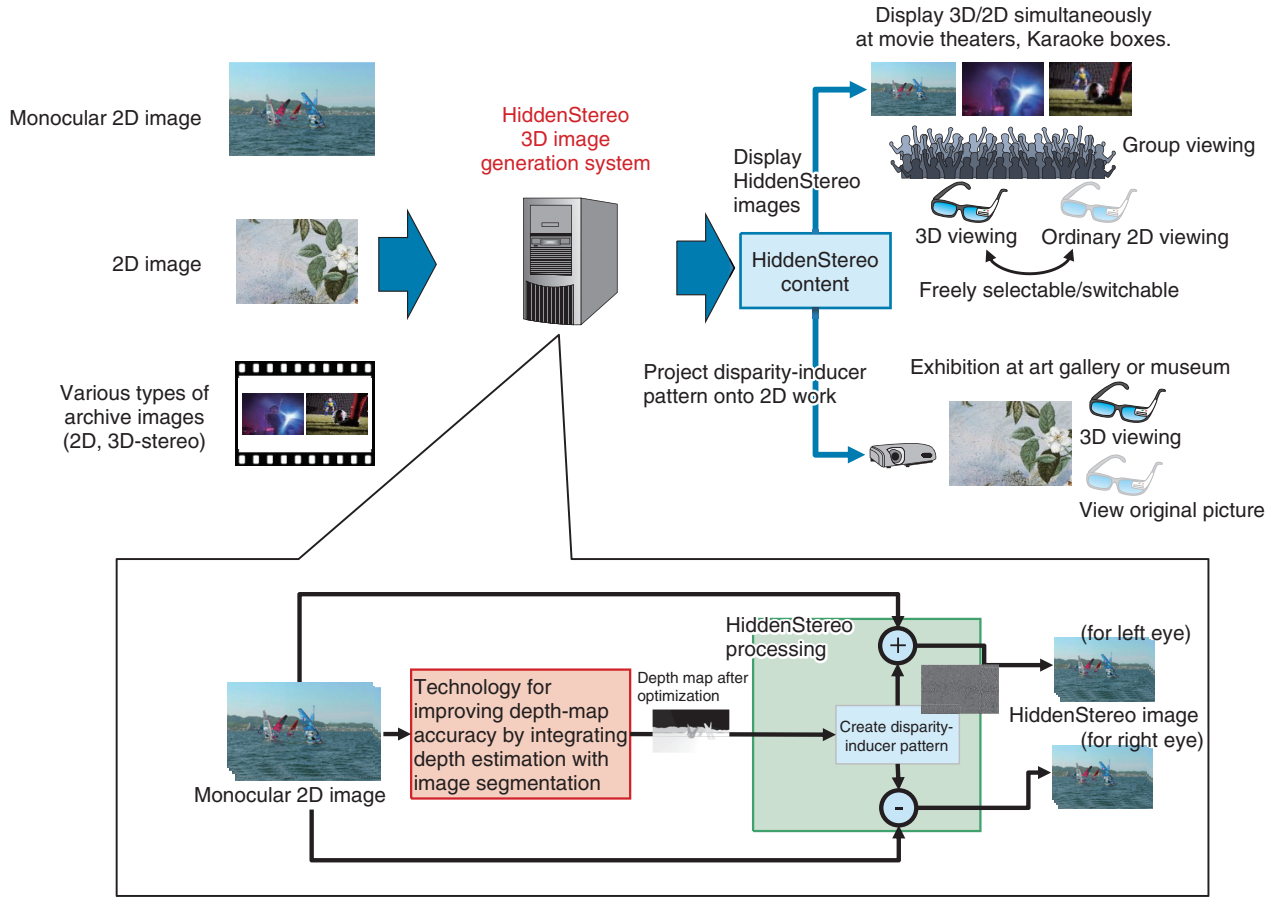

Fig. 4. HiddenStereo.

the above-mentioned technologies (**Fig. 4**).

HiddenStereo generates a disparity-inducer pattern from the original video and depth map, which provides depth information to human viewers. Images for the left and right eyes can be generated by adding or subtracting this pattern from the original image. When the left and right images are added together, the disparity-inducer patterns completely cancel each other out, leaving the original image, so that viewers without 3D glasses can see the 2D image clearly. Viewers with 3D glasses see the image with depth due to the effects of the disparity-inducer pattern.

This technology enables viewer-friendly 3D display, allowing each viewer to select how they want to view at any time, and all view the same display content. Since no special equipment is needed to display 2D and 3D at the same time, existing 3D display environments can be used as-is. Operational requirements for ordinary 3D video projection, such as presenting 3D and 2D video at different times, or preparing separate venues for 3D and 2D presentation are no longer necessary, which could reduce the operating costs for 3D video presentation.

By using our technology for improving depth-map accuracy, by integrating depth estimation with image segmentation, with HiddenStereo, we can convert not only new content captured with stereo cameras or created with 3D computer graphic production but also from 2D content produced in the past into 3D content.

4. Future developments

We introduced a media-processing technology we are developing for improving the accuracy of depth maps by integrating depth estimation with image segmentation, and a system using this technology to generate HiddenStereo images, enabling natural 3D viewing from monocular 2D image. We will continue investigation to further improve the speed and quality

of each of the component technologies through verification trials and other means to contribute to implementing businesses using natural interaction.

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Affect-perception Control for Enhancing a Sense of Togetherness for Remote Spectators

Takashi Sano, Motohiro Makiguchi, Hidenobu Nagata, and Hitoshi Seshimo

Abstract

The COVID-19 pandemic has affected the world of sports and entertainment by expanding the audience for spectator-less sports broadcasts and live-event distribution. In addition to the research NTT Service Evolution Laboratories has been conducting on remote transmission and reproduction of sense-of-presence for event venues, we are promoting research on elemental technology for capturing the emotional movements (affect) of remote viewers to provide what we believe is the emotional feedback needed for such viewers to share a sense of togetherness, interactivity, and excitement as spectators.

Keywords: affect, sense of togetherness, enthusiasm

1. Background

As the COVID-19 pandemic is currently restricting personal movement and face-to-face interaction, there has been rapid progress in creating remote forms of various human activities. For sports and entertainment, the broadcasting and live distribution of spectator-less events is increasing. However, it is not yet possible for remote spectators to experience the intensity and extraordinary feeling of being at a stadium or live venue.

NTT Service Evolution Laboratories has been conducting research and development (R&D) on technology for sensing the entire space of an event venue and transmitting and reproducing the on-site sense-of-presence and audience enthusiasm to remote live-viewing locations. The technology includes advanced real-time object extraction [1], ultrawide video composition [2], Advanced MMT[*1] for synchronous transmission of video and audio [3], and glassless three-dimensional video display that applies the principles of perceptual psychology [4]. However, participation at stadiums and live venues is restricted, and remote sites are not large like live-viewing locations. In a situation where the viewing site is shifting to small, independent locations, such as the home, it is not sufficient to simply convey the enthusiasm and intense moments of the actual site. Instead, a sense of togetherness and interaction among remote spectators can be used to enhance the sense of excitement.

We are therefore beginning R&D on affect-perception control for capturing the emotional responses of viewers using simple devices. By establishing elemental technology for that purpose, we intend to enable an experience in which even remote viewers can feel the thrill of watching an event together with many people in a stadium or live venue.

2. Affect-perception control

Affect-perception control can be broadly categorized into three types of technology: field[*2]-sensing

*1 Advanced MMT: MPEG Media Transport (MMT) is a media transport standard developed by the Moving Picture Experts Group (MPEG), a working group of International Organization for Standardization/International Electrotechnical Commission (ISO/IEC). Advanced MMT is highly realistic media streaming/synchronization technology developed by NTT.

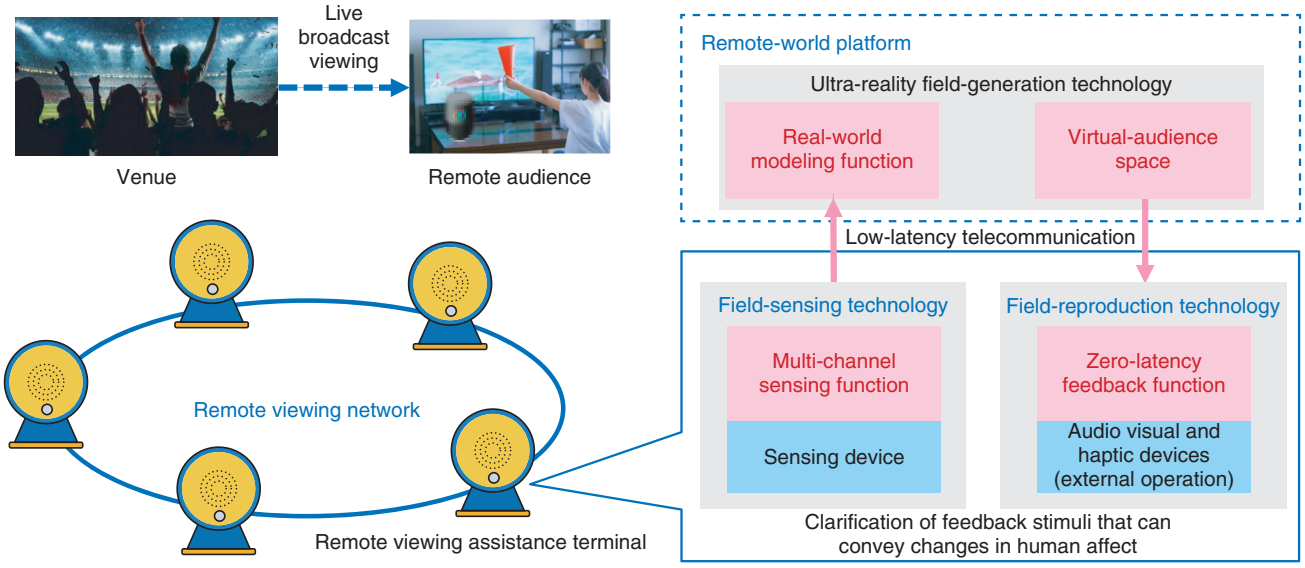

Fig. 1. Overview of affect-perception control.

technology for synchronous detection of the remote viewer's reactions and local situation, ultra-reality field-generation technology for creating a virtual-audience-space model for virtual relocation of a large number of remote viewers from any location in a spatially natural manner, and field-reproduction technology for zero-latency feedback of changes in the affect of other viewers in response to each other's states in the virtual-audience space (**Fig. 1**). These technologies are explained in the following sections.

2.1 Field sensing

Even when watching the same sports event, some people will follow the movement of a particular player while others are analyzing the overall situation from a wide view and still others are cheering in the audience around them. Thus, what people are paying attention to and the timing of changes in spectator affect differ from person to person. This is also true for other live entertainment events, e.g., when different audience members get excited at different songs or performances. The objective of our research is to achieve real-time sensing, visualization, and quantification of human affect with multi-channel sensing implemented by interworking among multiple sensing devices such as voice-acquisition devices (e.g., smart speakers, television (TV)-mounted cameras), person-sensing devices (e.g., air conditioners), and wearable devices (e.g., smart watches that measure vital signs).

Specifically, cameras and motion sensors are used to capture the viewing environment such as the position of the TV, pose of audiences, and line of sight of the viewer. Sensing is used to detect the degree of viewer concentration and which part of the viewing content has the viewer's interest. Then, the viewing content and changes in the viewer's movements and voice are analyzed to learn what types of situations are associated with changes in viewer affect. These changes in a viewer's affect can be measured in more detail by sensing internal body signals, such as body temperature and pulse, at the same time as measuring external changes such as movement.

2.2 Ultra-reality field generation

This technology implements a virtual-audience-space function for real-world modeling that turns the viewer's environment into a virtual-spatial model and fills the space with many remote viewers in a natural manner. Establishing this technology will make it possible to aggregate the viewer-affect information collected with the technology described in the previous section and categorize viewers by affect to construct an audience space that enhances enthusiasm. It may also be possible to increase the interest of viewers categorized as showing less interest in the content when watching alone by placing them in an audience

*2 In this article, "field" means the person's affect and the space around him/her.

Fig. 2. Experimental space.

space with highly enthusiastic viewers. Analysis of sports action and live content to synthesize virtual cheering (fake crowds) according to the exciting parts would make it possible to construct special spaces that create the impression of audiences of tens or even hundreds of thousands cheering in stadiums or event venues that accommodate just a few thousand spectators or even no audience at all.

2.3 Field reproduction

The data for the virtual space described above are combined with information that creates a feeling of the presence of other viewers, such as video, sound, and shadows, to implement a zero-latency feedback function that augments change in viewer affect and enthusiasm. To increase the sense of togetherness among remote viewers by implicitly creating the sense of cheering together side-by-side, we are developing spatial-presentation technology that focuses on touch and other senses in addition to visual and auditory senses. The timing of triggering affect control is also important. Together with technology for bi-directional transfer of a huge amount of sensory data with zero-latency, we are also engaged in R&D on technology for autonomous presentation of information that suggests changes in affect by predicting the next reaction either from changes in viewer affect or context changing in content at the viewer's location instead of transmitting all the sensory data to each location.

To promote R&D on affect-perception control, we constructed an experimental space to verify its effectiveness (**Fig. 2**). Taking the viewing of a sports event in the living room at home as the use case, we verified the degree of influence on change in viewer affect as well as an optimal sensing and feedback method. We did so by virtually expanding the living room into a virtual connected remote live-viewing venue where multiple spectators gather according to excitement in the game and by presenting performances that produce a reaction by adding effects to video in accordance with the appearance of viewer emotion detected by sensing.

3. Future prospects

For future work, we will promote R&D for creating new value in the world of remote activities by conducting verification experiments in various real-world situations such as viewing sports events and entertainment distribution with the objective of establishing affect-perception control.

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Visible-light Planar Lightwave Circuit Technology and Integrated Laser-light-source Module for Smart Glasses

Toshikazu Hashimoto and Junji Sakamoto

Abstract

NTT Device Technology Laboratories has applied planar lightwave circuit technology, which is used to integrate optical circuits on a planar substrate for optical communication devices, for use in the visible-light domain, enabling the development of dramatically smaller optical systems using all three primary colors of light (RGB: red, green, and blue). We applied this technology to an ultra-compact RGB laser-light-source module that is small enough to be installed on the temples of glasses, making smart glasses feasible.

Keywords: smart glasses, visible-light planar lightwave circuits, laser-light-source module

1. Introduction

As information and communication technology has progressed, new lifestyles are emerging like never before through information, e.g., online distribution of music and video and chat services. This information is brought to us through information terminals connected to networks. Various information terminals, such as personal computers, smartphones, and more recently, devices such as smart speakers, are being used for many daily-life situations. However, the information we receive is limited to where the terminal or other device is, and smartphones are not an exception to this. With smartphones, our access to information is possible only by peeking through a small "window" (screen). If we could develop information terminals that we could use in a more natural way, lifestyles would become richer and freer without such limitations.

The optical circuit technology introduced in this article is intended for application to smart glasses, which will provide access to visual information in a more natural way, as discussed above. Smart glasses are display devices that should feel comfortable, like putting on ordinary glasses, and improve on current goggle-shaped head-mounted display devices that are being used for virtual reality, augmented reality, mixed reality, and other applications, which are generically called extended reality. Various levels of display performance are possible, but to provide an immersive experience, as with augmented reality, technology for providing high resolution and a wide field of view is necessary. Having smart glasses look like ordinary glasses requires the components to be very small, so technology is needed to achieve both optical characteristics and miniaturization. NTT Device Technology Laboratories developed the above optical circuit technology for dramatically reducing the size of optical systems that handle light in the RGB (red, green, and blue) color space. This technology is called the RGB coupler and is suitable for the type of smart glasses describe above [1, 2]. This article introduces the RGB coupler and its application to an ultra-compact RGB laser-light-source module for smart glasses.

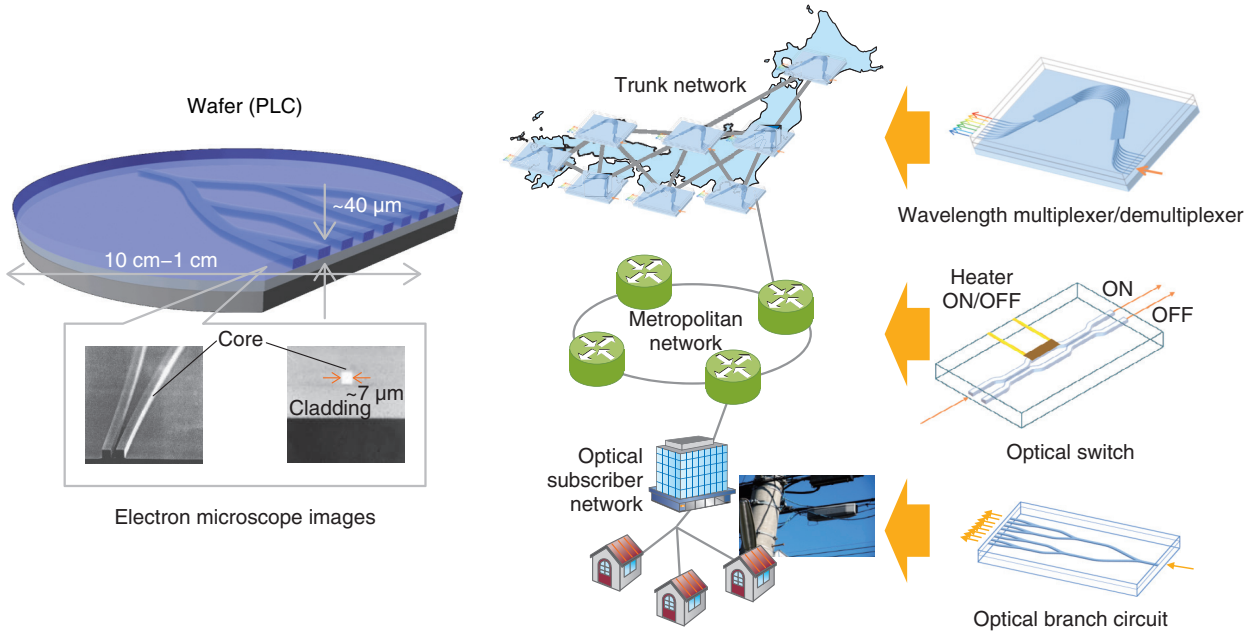

Fig. 1. PLCs and applications in optical fiber communications.

2. Visible-light planar lightwave circuit technology

For optical fiber communications, NTT is conducting research and development on a component technology called planar lightwave circuits (PLCs)*, in which optical circuits are integrated on a silicon substrate, similarly to electronic integrated circuits. These optical circuits are fabricated using silica glass, the same material for optical fiber, and are composed of paths several microns wide called cores. The cores have a higher refractive index than the surrounding material, causing the light to follow them (optical waveguide structures). Circuits can be built to branch, interfere with, or control the phase of the light. PLC technology is used in devices for optical fiber communications, such as optical splitters and wavelength multiplexers/demultiplexers [3] (**Fig. 1**). Infrared lasers with wavelengths, such as 1.55 μm, are used for optical fiber communications, so the laser technology for such wavelengths and optical circuit technology to manipulate them (e.g., wavelength multiplexers/demultiplexers) have been developed. The wavelengths of visible light are in the range of 0.4 to 0.7 μm, and since mass production of green semiconductor lasers was achieved around 2009, it has been possible to use all three primary colors. Just as visible-light light-emitting diodes came into general use over a period of more than ten years, visible-light lasers are expected to become common. When this occurs, technology to provide stable optical systems will be important for various applications using laser-light properties such as interference. NTT is applying PLC technology in the visible-light domain to develop such systems. Applications for this technology include optical light sensing and optical quantum-information processing. The RGB coupler is another application of this technology.

3. Retina-scanning laser eyewear and RGB light source

Before describing the RGB coupler, we first describe scanning laser eyewear. As the name suggests, laser eyewear refers to a glasses-type display device that uses laser light [4]. Laser light has the useful property of not diverging over distance, so that just like with a laser pointer, when a laser ray hits a screen it makes a clear, bright spot, regardless of the distance to the screen. By scanning this point of laser

* PLC: Optical integrated circuits fabricated using a technology combining optical fiber manufacturing technology and semiconductor integrated circuit technology. Circuits are fabricated mainly with quartz glass, so they are compatible with optical fiber materials (low optical losses when connected together). PLC is used as a component technology for optical fiber communications.

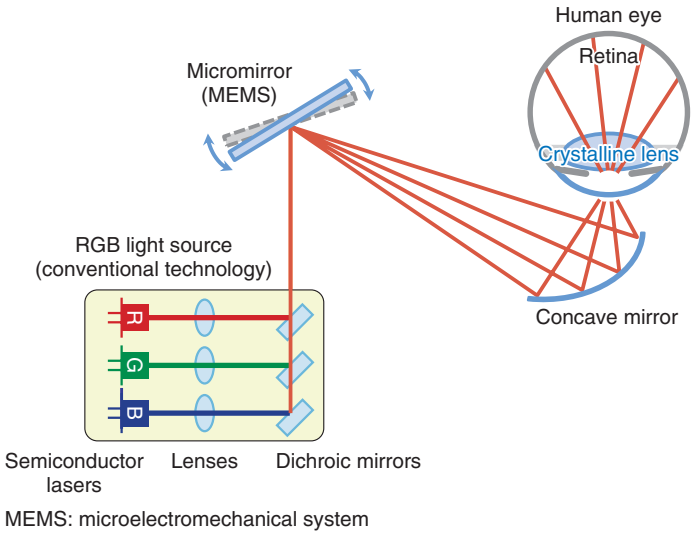

Fig. 2. Principles of retinal-projection laser eyewear.

light across the screen while changing the brightness, a focused image can be displayed regardless of the distance to the screen. Scanning laser eyewear applies this principle to the human eye, using the retina as the projection screen. The crystalline lens of the human eye must change shape to form an image (focus) on the retina, but with a scanning laser, a focused image is projected on the retina regardless of the shape of the lens, so an image can be obtained regardless of visual acuity. This system is extremely simple, as shown in **Fig. 2**, and composed of just microelectromechanical system mirrors that scan the laser light source and another mirror that directs the laser light through the pupil. Note that the intensity of the laser is adjusted to a safe level, which is roughly 1/1000 that of a laser pointer. However, current components for such a configuration are not small enough for glasses-type laser eyewear. The laser-light-source module is a particularly complex structure, involving lenses or mirrors to combine the outputs from the three (RGB) semiconductor lasers, and is difficult to miniaturize (Fig. 2, lower left).

4. RGB coupler and RGB laser-light-source module

NTT Device Technology Laboratories has focused on the lens and mirror structure as the optical components of the laser-light-source module described above and has significantly reduced the size of the module by applying visual-light PLC technology (**Fig. 3(a)**). Visible light has a short wavelength, less than half of those used for optical fiber communications, so we investigated all aspects of optical-circuit elements. We developed a new wavelength multiplexer for the RGB coupler, which has the smallest chip size yet achieved. **Figures 3(b)** and **(c)** respectively illustrate the operation of a conventional wavelength multiplexer and our new wavelength multiplexer. When two light paths (optical waveguides) are brought together, light is transferred from one waveguide to the other due to a kind of resonance, and this is called a directional coupler. The length of the directional coupler required to transfer signals through resonance depends on the wavelength, so by matching the period of the transition length, light can be combined in a single waveguide (Fig. 3(b)). At NTT, we have taken this a step further by placing a waveguide of a different width between them and found a width that simultaneously satisfies both resonant and non-resonant cases, depending on the wavelength (Fig. 3(c)). Using this configuration, we can transfer only a specific wavelength of light to the other waveguide without the need to match the period of the transition length, and light can be combined into one waveguide in a distance approximately one third of the conventional directional coupler. The light transmittance of the RGB coupler is shown in **Fig. 4**. The RGB wavelengths, shown in the figure with dotted lines, have high transmittance, indicating that favorable characteristics can be achieved. A chip of the RGB coupler is shown in **Fig. 5(a)**. The chip

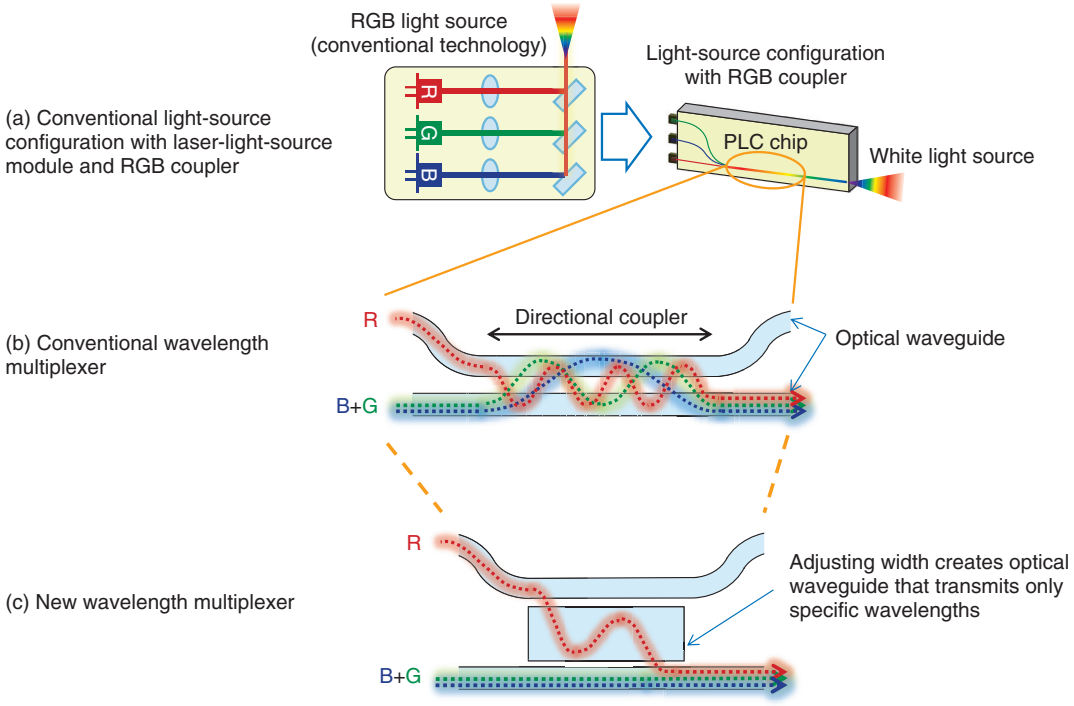

Fig. 3. Operation of conventional and new wavelength multiplexers.

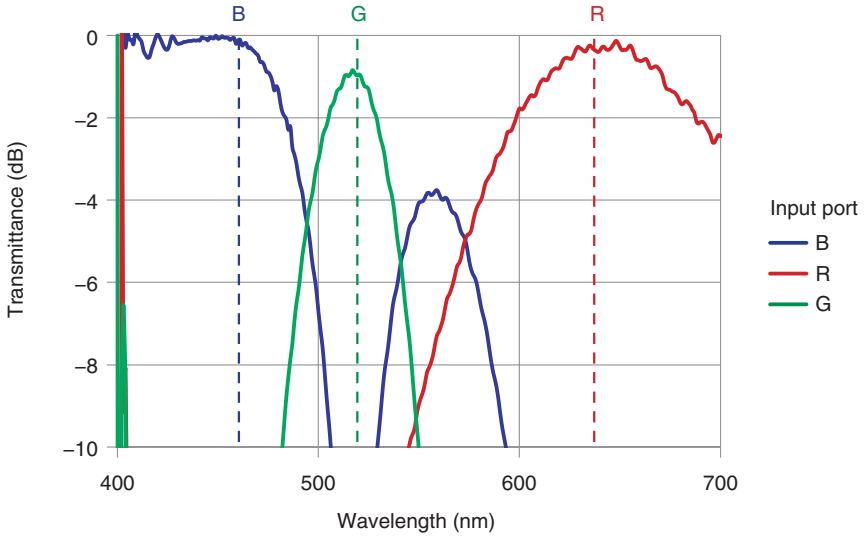

Fig. 4. RGB coupler transmittance.

size is 2.1×3.5×0.5 mm, and to the best of our knowledge, it is the smallest RGB coupler chip to date. NTT Device Technology Laboratories has also collaborated with TDK Corporation to implement a packaged optical light-source module (**Fig. 5(b)**). From this collaboration, we were able to fabricate the smallest RGB laser-light-source module (5.5×8×2.7 mm) by combining the semiconductor laser chips on

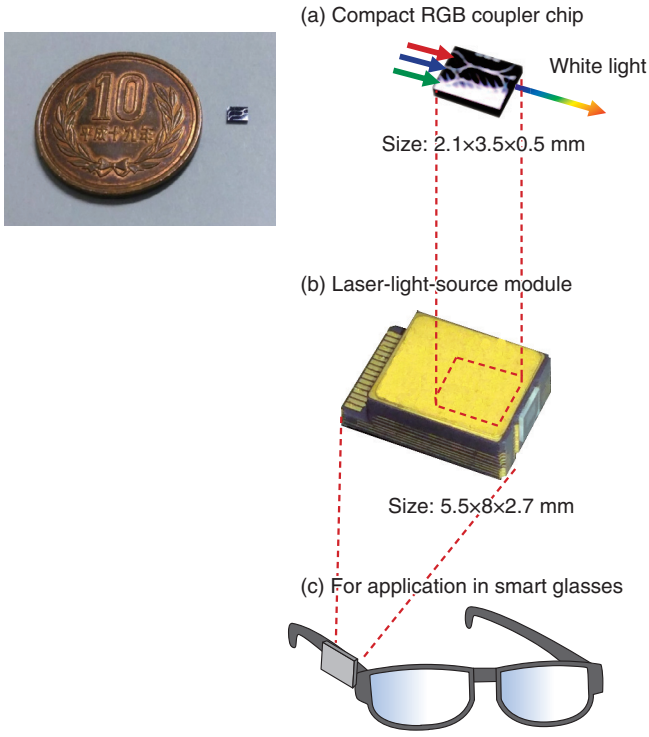

Fig. 5. Fabricated RGB coupler and laser-light-source module.

subcarriers with TDK's technology for aligning and fixing the lasers and optical waveguide ends with an accuracy of better than 1 μm in a very short time. The size of this ultra-compact RGB laser-light-source module is approximately one twentieth that of earlier RGB light-source modules using lenses or mirrors. It is comparable to the width of the temples of glasses and is suitable for implementing glasses-type laser eyewear, as shown in **Fig. 5(c)**.

Large parts of the environment in which we live are now being produced by information. As the smartphone has had a huge influence on our lives, the technology introduced in this article will contribute to the development of display devices that can be used anywhere and much more naturally. This will contribute to creating richer environments in which to live.

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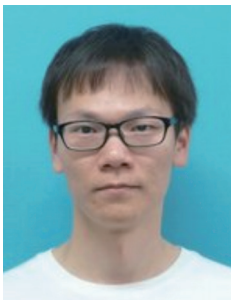

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Fine-grained Hand-posture Recognition for Natural User-interface Technologies

Yuki Kubo

Abstract

NTT Service Evolution Laboratories is conducting research on user-interface technologies to improve system usability. As part of this research, we are focusing on new input methods that will be an important element of next-generation information devices, and in particular, we are researching hand-posture recognition technology to be used to implement input for glasses-based devices. This article describes initiatives related to this research.

Keywords: user interfaces, sensing technologies, hand-posture recognition

1. Introduction

Information devices are used to display information to users in all types of situations and have become indispensable in daily life. Most of these devices are either displays installed in public spaces or portable mobile devices such as smartphones. Many companies are also researching a new type of wearable information device that users will wear like glasses, referred to as smart glasses or augmented reality glasses. In contrast to previous devices, these glasses-type devices have characteristics that display information layered directly over the user's field of view.

Displaying information directly over the user's field of view enables this type of device to layer all types of information over the real world, presenting different information to each user. Information in public spaces, such as train stations and parks, has conventionally been presented through information displays that exist physically, such as signage installed in various locations in a train station to give directions, displaying the same information to everyone. However, with the ability of glasses-type devices to display different information to each user, all types of information that previously had a fixed existence in the real world can change dynamically to a form suitable for each user. The information each user needs can be displayed to him/her, and the amount of information displayed can also be adjusted for the comfort of each user.

We are now connected to information more than ever before, so with information layered over the real world through glasses-type devices, it will be increasingly important to have an input method for such information, similar to how we input on a smartphone screen. This article introduces a technology for recognizing fine-grained hand postures, which is currently being investigated and will be necessary for developing natural user interfaces.

2. Related work

One input method that is promising for glasses-type devices involves gestures, i.e., using the state or motion of the hands. To make gesture input possible, the hand gesture has to first be recognized using a camera [1]. However, there are issues with using cameras: limited range where recognition is possible due to camera position and field-of-view and recognition difficulty if anything obstructs the camera's view (i.e., occlusion problem).

How hand gestures will be recognized is important, but the design of gestures used to perform input is also important. One can imagine using large arm

movements up, down, left, and right, and having the arms raised for long periods of time as types of hand gestures, but there are several problems with such gestures. Large movements or holding the arms up continuously will increase fatigue and place an increasing burden on the user over time. Large arm or body movements also have disadvantages in terms of social acceptance, such as being distracting to people nearby, being difficult when people or other obstacles are in close proximity, and allowing people nearby to see the gestures, thus allowing them to determine what the user is doing. As one solution for these problems, NTT Service Evolution Laboratories is focusing on input methods that use smaller hand gestures to reduce the burden on users and is researching a fine-grained hand-posture recognition technology that uses sensors attached to the back of the hand. Next, we introduce this technology, which is called AudioTouch [2], based on active acoustic sensing.

3. Technology overview

AudioTouch uses ultrasound waves through principles such as ultrasonography. It detects changes in the structure (e.g., bones, muscle, and sinew) in the back of the hand and uses them to estimate hand postures. Objects generally have their own resonance properties, which depend on features such as shape, material, and boundary conditions. A previous study [3] focused on how the resonance properties of an object change due to changes in its boundary conditions when the user touches it. They proposed a method for making touch interfaces from objects with sensors attached that recognize when the user touches the object. In contrast, AudioTouch focuses on changes in resonance properties due to changes in the shape of the hand itself due to movement of fingers and hands, including the internal structure of the hand. When the user changes his/her hand and finger postures, the resonance properties of the hand change due to the movements of parts of the hand, such as skin, bones, and muscles. By measuring the differences in these properties, the hand and finger postures can be recognized. Changes in resonance properties can be measured by sending oscillations (ultrasound waves) through the object and measuring the frequency response. AudioTouch observes the frequency response of the back of the hand on the basis of this concept to recognize changes in hand and finger postures. Specifically, it uses two piezoelectric sensors attached to the back of the hand (**Fig. 1**). The first emits ultrasonic waves both on the surface and inside the hand, and the other measures the ultrasonic waves propagated over the surface and in the interior of the hand. The captured sound waves are analyzed to obtain the frequency response, and this is used to generate features, which in turn are used with machine learning to recognize hand and finger postures.

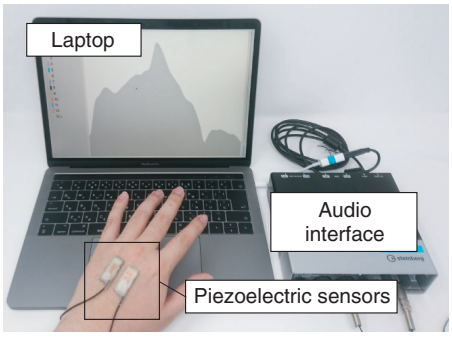

Fig. 1. AudioTouch components.

We conducted experiments to evaluate whether AudioTouch could recognize three gesture sets (**Fig. 2**). The three gesture sets were: one in which the thumb touches each of the finger joints, one in which the thumb is moved left, right, up, and down, and one in which a finger on one hand is used to touch the palm of the other. We also explored whether levels of pressure applied when pressing the thumb and other fingers together could be differentiated into two levels (i.e., strong and weak). Example applications for these gestures include using the palm as a touch-sensitive number keypad or for selecting menu items.

4. Conclusion

In this article, technologies for performing input with glasses-type devices were discussed and current initiatives in developing technology for recognizing fine-grained hand posture, as an element for such technologies, were presented. There are still technical and social issues to be resolved, and NTT Service Evolution Laboratories will continue to advance this research.

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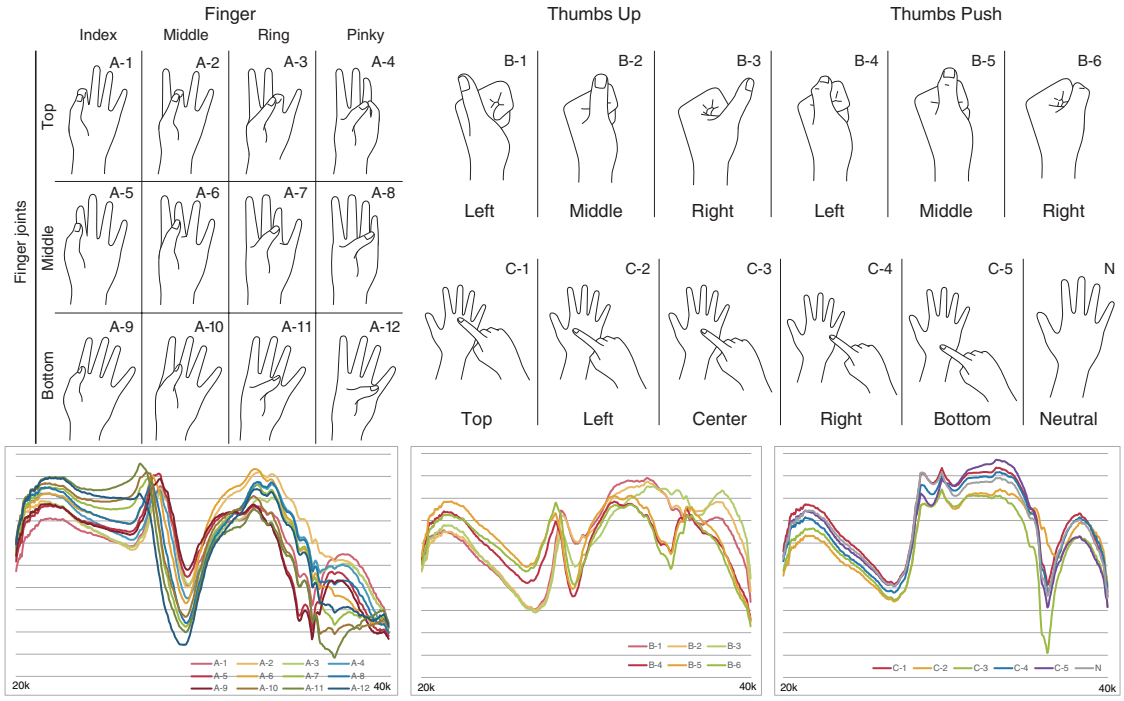

* Waveforms are examples of waveform-data averages for a given user and label.

Fig. 2. Examples of gesture sets and gesture waveforms.

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Information-display Method for Reducing Annoyance by Gaze Guidance

Ryohei Saijo, Tae Sato, Shin-ichiro Eitoku, and Masahiro Watanabe

Abstract

We are investigating methods of displaying action information to users of smart glasses and other wearable information devices that are worn daily as they try to attain goals during daily activities. Forcefully presenting information to a user may annoy him/her and discourage him/her from continuing to use the device, but access to information is uncertain if not forced. To solve this problem, we devised a forced-information display method that reduces annoyance yet ensures that information is received by giving the user the feeling that the act of reading was him/her choice. We also evaluated the possible effectiveness of the method.

Keywords: information presentation, gaze guidance, peripheral vision

1. Information display that interrupts daily activities

Research and development on wearable information devices has been active. Users can benefit in various ways by receiving information from a display system that presents timely information via such devices. Consider an example in which a device displays "Let's take the stairs." when a user that has not been doing enough exercise arrives at a place where there is an elevator and a staircase. The idea is that the user can improve a daily habit by immediately noticing the suggestion and following it (**Fig. 1**). However, the information is useless if it is displayed when the appropriate time has passed (when the user has already entered the elevator, for example). It is therefore important that the user accesses the information with certainty when it is displayed. However, if the user's attention is obtained forcefully to achieve that certainty, the user may regard the display as interrupting him/her current activity. Such feelings might cause the user to stop using the information-display system.

In scenarios for improving daily habits, the information-display system can be used as a tool for user self-improvement toward personal goals. To support daily improvement, the system must continuously and effectively display information to the user. Our research therefore has the objective of implementing an information-display method that creates a low degree of annoyance for the user when information is displayed yet ensures a high certainty of information access [1].

2. Current technology

Much research has been conducted on methods for displaying interrupt information. For example, if the user ignores a prompt to read information, a more forceful prompt is displayed, and the information is finally superimposed on the work screen if not accessed [2]. This approach increases the certainty of the information being accessed but increases the user's feeling of annoyance. One way to reduce the interruption effect is to estimate the degree of rejecting interrupt information from the device operation history and using the data to display information at

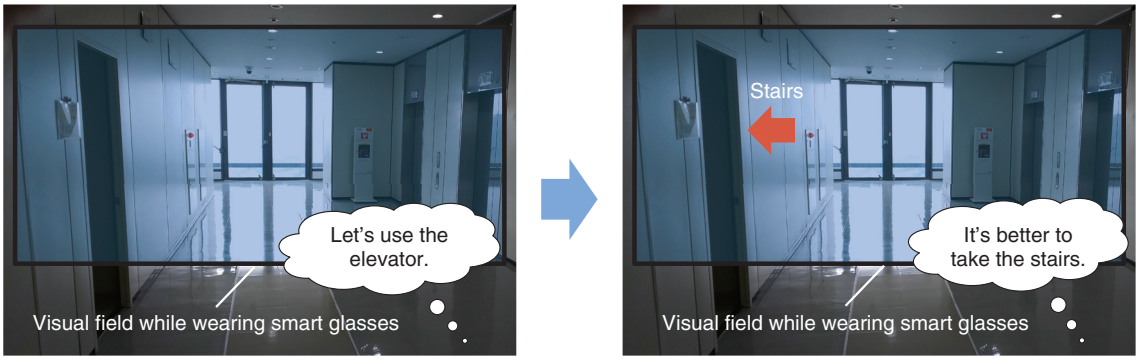


Fig. 1. Example of interrupt information display when using smart glasses.

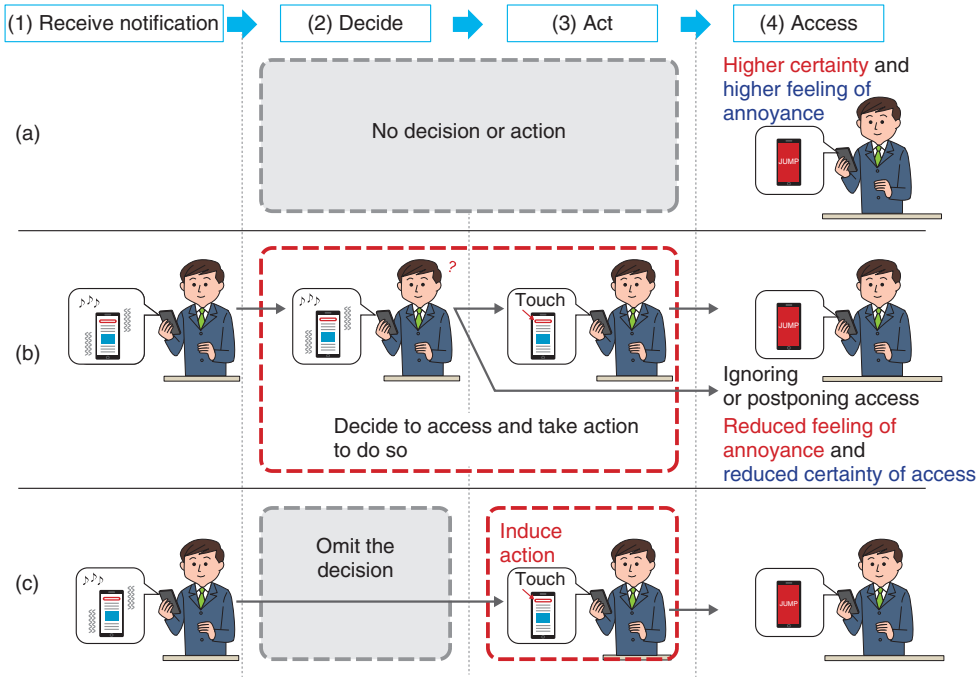


Fig. 2. Information-access process.

times when the degree of rejection is low [3]. While this method reduces disruption of the current task, it does not allow timely presentation of information. It is thus difficult to both reduce the feeling of annoyance and increase the certainty of information being accessed. Although previous research evaluated interference with the user's work, how the user feels about the distraction has not been studied. The feeling of annoyance may be high, even if there is no actual interruption to the original task. We must therefore consider the user's feeling of annoyance.

3. Process leading to information access

The process that results in reading information has four steps: 1) receive notification, 2) decide to read, 3) take action to read, and 4) read (**Fig. 2**). We focused on steps 2 and 3: decide and take action, and considered how the presence or absence of those steps affect a user's feeling of annoyance and the certainty of access.

Consider the process illustrated in Fig. 2(a) to be a display method that prioritizes the certainty of access.

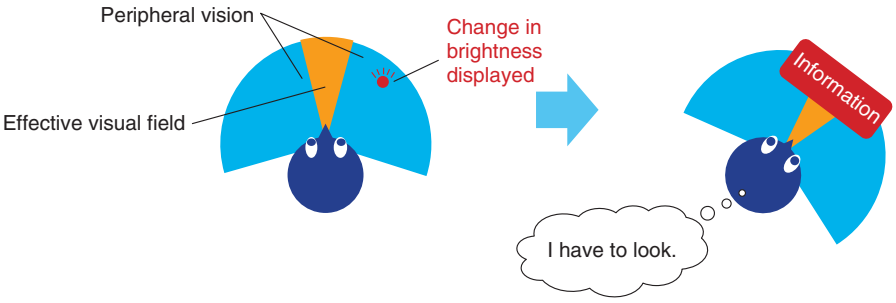


Fig. 3. Pseudo-choice method with gaze guidance.

For example, the information is displayed at the location of the user's gaze, so the user does not decide to attend to the information and does not have to take action to see the information. This method is considered to result in a high certainty of access, but it may produce a greater feeling of annoyance. The method in Fig. 2(b), on the other hand, can prioritize reduction of the feeling of annoyance. With this method, the user decides to see the information and takes action to see it. For example, the user first sees a prompt then touches an icon to view the information. This method may reduce the feeling of annoyance but reduces the certainty of access because the user often postpones access at the decision step.

4. Pseudo-choice interrupt display method

We hypothesized that the certainty of information access can be improved by omitting the decision step while reducing the feeling of annoyance of information access by inducing the action step. Based on this hypothesis, we propose a pseudo-choice method in which the decision is omitted and the action to access is induced by the information-display system (Fig. 2(c)).

As one specific implementation of the pseudo-choice method, we investigated a gaze-guidance technique that uses the change in brightness of the peripheral visual field, which is sensitive to brightness and movement (**Fig. 3**). This technique guides the user's gaze by presenting a brightness change in the visual periphery to induce the action step without the decision step.

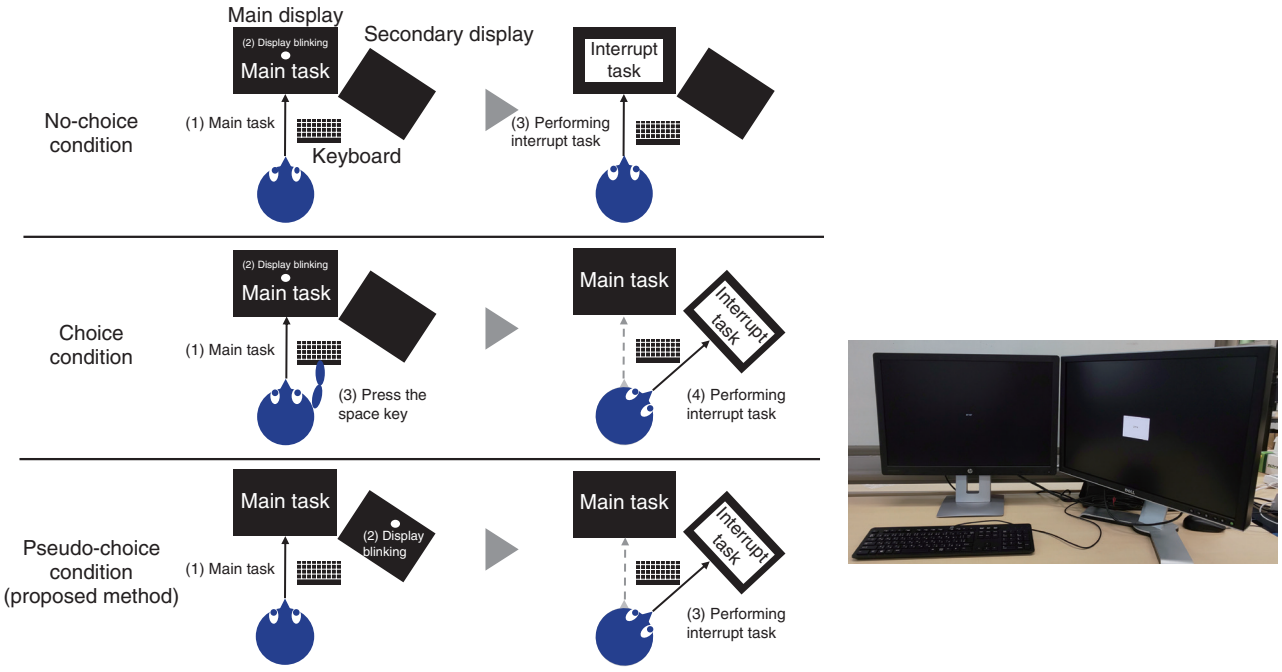
5. Evaluation of the proposed method

Adapting a dual-task constructed from a main task and interrupt task, we evaluated the effectiveness of the pseudo-choice method by comparing three different interrupt-task display methods that correspond to the methods in Fig. 2 (**Fig. 4**). The experiments first focused on evaluating the reduction in the feeling of annoyance. The main task corresponds to daily activities such as watching videos, and the interrupt task corresponds to displayed suggestions such as "Let's get up for a while." In daily life, we repeatedly alternate between concentrating on one activity then moving on to another activity. To reproduce such a situation in the experiments, we used two-digit addition problems to serve as the main tasks and repeatedly alternated between the situation of solving the problem (activity) and moving on to the next problem (break in activity). To simulate user accessing details of interrupt information, we used the act of multiplying a two-digit number by a one-digit number to serve as the interrupt task.

The participants were 10 males and females; age ranging from 20s to 50s. The participants were instructed to solve as many problems as possible as they are presented sequentially to encourage concentration on the main tasks. They were instructed to also solve the interrupt task problems as they appeared. After the experiments, the participants filled out a questionnaire asking about their feeling of annoyance for each experimental condition on a five-point scale. Statistical analysis of the evaluation results indicates that the feeling of annoyance was greater for the no-choice and pseudo-choice conditions than for the choice condition.

The average scores from the questionnaire (**Fig. 5**) indicate that the no-choice and pseudo-choice conditions produced greater perceived annoyance than did the choice condition, and that the no-choice condition produced greater perceived annoyance than did the pseudo-choice condition.

These results indicate that the pseudo-choice



(a) Experimental conditions and schematic diagrams

(b) Experimental setup

Fig. 4. Experimental conditions and setup.

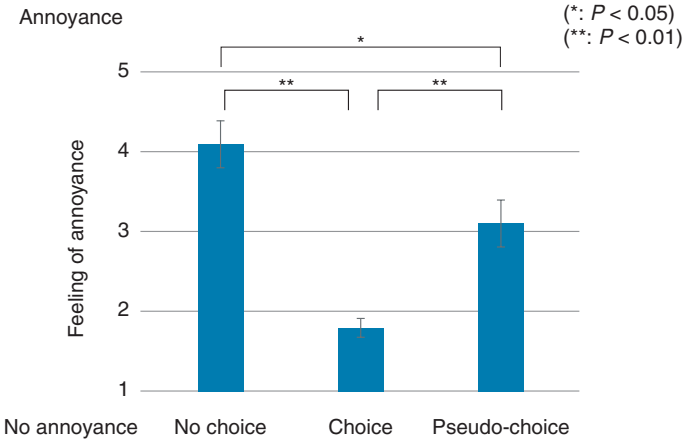


Fig. 5. Average scores from questionnaire on degree of annoyance.

condition can reduce the user's feeling of annoyance relative to the no-choice condition, suggesting that our pseudo-choice method has the potential to reduce the feeling of annoyance from the displaying of interrupt information. The choice condition resulted in the least feeling of annoyance, confirming the potential of methods that take into account user decision and action to reduce the feeling of annoyance.

6. Future development

In this research, we focused on the movement of the user's line of sight as voluntary action for reading information and confirmed that inducing a gaze

movement may result in reducing annoyance of displaying information that interrupts the current task. The objective of future work is a detailed examination of factors that reduce the feeling of annoyance and implement a system for displaying information to improve the every-day behavior of users.

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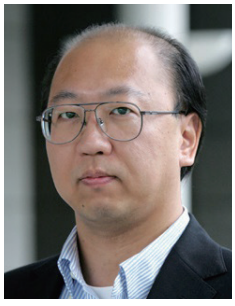

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Presenting Material Properties with Mid-air Pseudo-haptics

Takahiro Kawabe

Abstract

With the development of image presentation and behavioral-data-acquisition technologies, interaction between a virtual object and user has become commonplace. This article introduces mid-air pseudo-haptics, a technology to provide haptic perception of material properties to the user when the virtual object is manipulated by the user's actions. With this technology, the virtual object is deformed by the user's actions, and the impression of the object's softness is controlled by its deformation pattern. In the future, we will develop technology to provide richer perceptual material properties to virtual objects.

Keywords: mid-air pseudo-haptics, material perception, illusion

1. Motivation

In Hollywood science fiction movies, we often see scenes in which the main character in a futuristic world skillfully manipulates images in the air. What would be the haptic nature of images floating in the air? This simple question is the motivation for this study. Mid-air image representation is no longer science fiction but is now possible with optical devices and head-mounted displays. NTT's "Kirari!" immersive telepresence technology is another means of displaying images in the air. Research on presenting haptic sensation to aerial images (virtual objects) is being conducted. Various methods have been proposed, but most use devices that provide physical haptic sensations.

In this study, we investigated the possibility of manipulating the material properties of virtual objects by changing their appearance in response to user actions. The user obviously cannot directly touch a virtual object; therefore, we thought that it would be possible to provide haptic properties to a virtual object by using perceptual illusion. Specifically, we investigated whether it would be possible to provide an illusory haptic sensation to a virtual object when we see a causal relationship between the user's manipulation of the object and change in the object's appearance.

2. Pseudo-haptics

Before explaining our research in detail, let us consider the pseudo-haptic effect. Suppose a user moves the cursor displayed on the computer screen with the mouse. Now, suppose the user keeps moving the mouse in the same manner, but the cursor suddenly slows down. Studies have shown that this type of slowdown leaves the user with a sense of resistance and increases the perceived weight of the cursor. This effect is called pseudo-haptics [1]. Pseudo-haptics is an illusion that involves multiple sensory modes including vision, touch, perception, and proprioception, but the effect of vision on other modalities is particularly critical. Pseudo-haptics can manipulate impressions of the shape and stiffness of virtual objects, as well as their weight and resistance.

3. Mid-air pseudo-haptics

The pseudo-haptic sensation generated when the user touches a haptic presentation device has been investigated [2]. In our study, we investigated whether it would be possible to generate pseudo-haptic sensation when there is no physical contact. We call such an effect *mid-air pseudo-haptics* [3]. To achieve this effect, two problems had to be solved. The first was how to track the user's hand movements, which

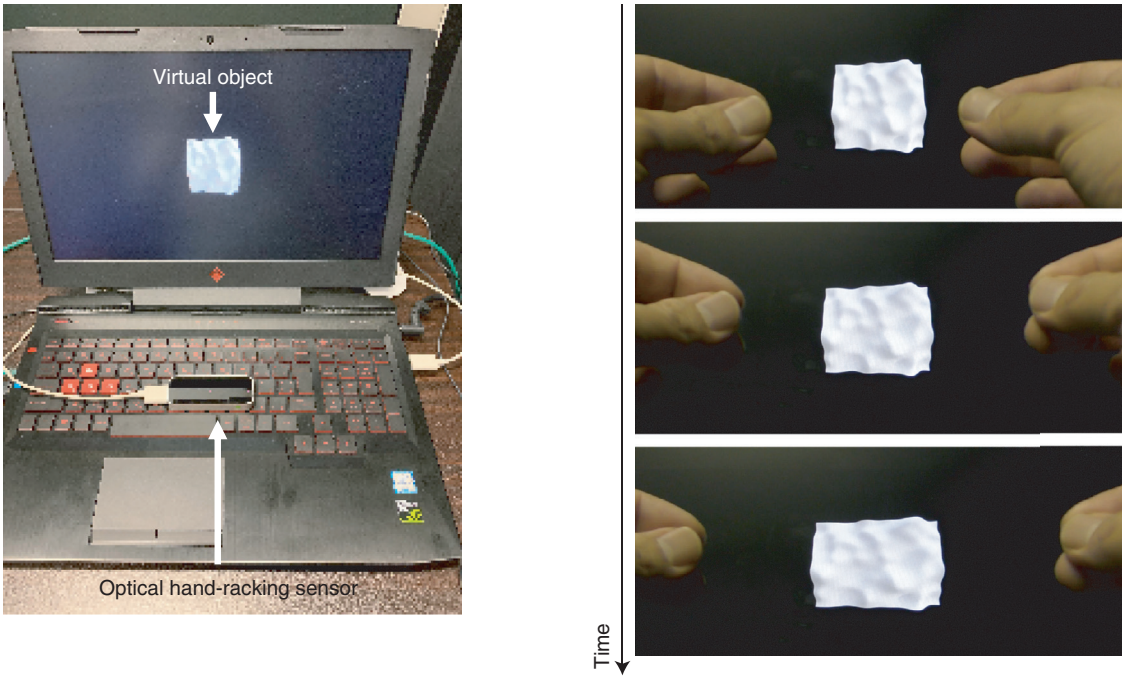

Fig. 1. (a) Experimental setup. Hand movement is tracked using an optical hand-tracking sensor, and the virtual object is deformed in accordance with the movement. (b) Deformation of the object resulting from hand movement.

was easily solved using an optical hand-tracking sensor (**Fig. 1(a)**). The second problem was what kind of changes in the virtual object associated with the tracked hand motion would create the perception of material properties. This problem was not straightforward because it involves human perceptual characteristics but is a very interesting question.

4. Key points of this study

We addressed mid-air pseudo-haptics by focusing on the following three points.

4.1 Poisson effect and Poisson ratio

We investigated the user's action of pulling a virtual object. When a user applies tension by pulling an elastic object in the horizontal direction, a compressive force acts on it in the vertical direction. For example, when we pull on a rubber object, it stretches in the direction of the pull but decreases in thickness at the center. This phenomenon is called the Poisson effect. We devised a system in which a virtual object stretches horizontally according to the movement of the hand when the user makes a pulling action in that direction (**Fig. 1(b)**). At the same time, the object deforms vertically according to the Poisson's ratio, which is the ratio of the strain in the material in the direction of the applied force to the strain occurring in the direction perpendicular to that direction. In the natural world, the Poisson's ratio generally does not exceed 0.5. We investigated how the Poisson effect affected the perception of the stiffness of a virtual object by varying the Poisson ratio applied to the object's deformation.

4.2 Ratio of hand movement to object deformation

Previous research [4] on pseudo-haptics has shown that the smaller the ratio of the amount of change on the screen to the amount of action by the user, the more resistance and heaviness is perceived. In our study, we varied the ratio of the amount of deformation of the virtual object to the amount of action taken by the user to pull the virtual object and investigated the relationship between this ratio and perceived stiffness of the virtual object. When this ratio becomes larger, the amount of deformation of the virtual object becomes larger for the same amount of movement.

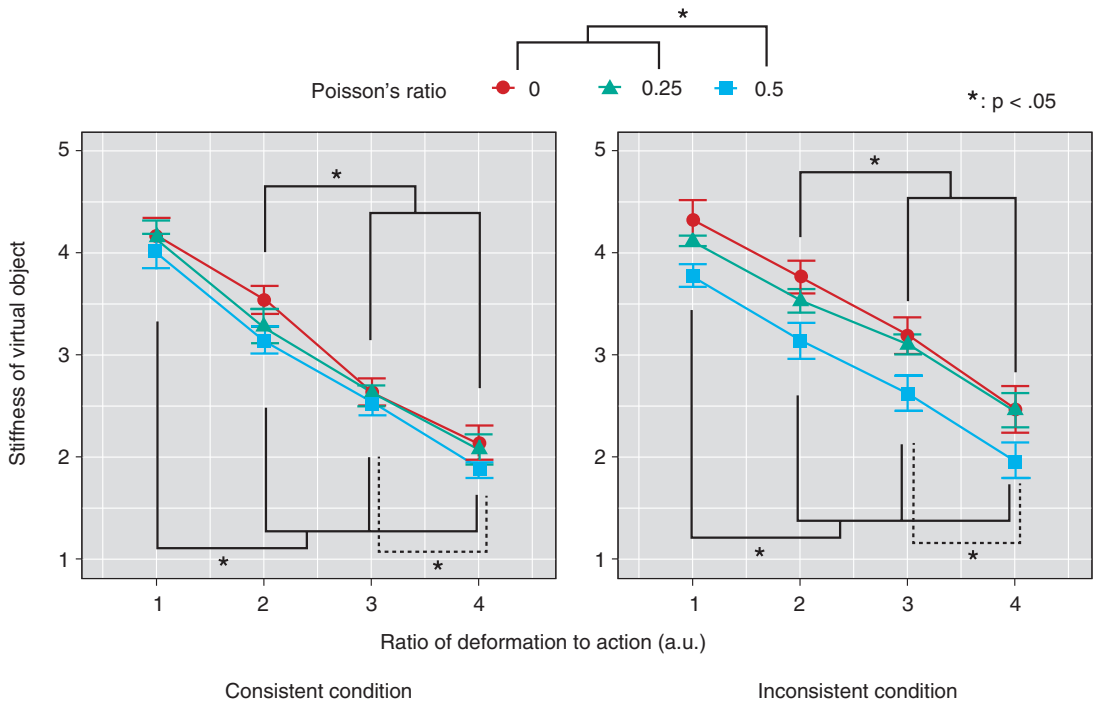

Fig. 2. Experimental results.

Therefore, the perceived softness of the object should increase accordingly.

4.3 Consistency between action and expected deformation

When a user pulls a virtual object horizontally, and the object deforms horizontally in response, the relationship between action and deformation is consistent. However, it is not clear whether the consistency of action and object deformation is necessary to manipulate the perceived material properties of an object. We addressed this issue by investigating experimental conditions for manipulating the consistency of action and object deformation, i.e., consistent and inconsistent. Under the consistent condition, when the user pulled the object horizontally, the object extended horizontally. Under the inconsistent condition, when the user pulled the object horizontally, the object contracted vertically.

5. Experimental results and discussion

Figure 2 shows the results of an experiment in which the stiffness of a virtual object was evaluated on five levels of Poisson's ratio. When the object had a Poisson's ratio of 0.5, it was judged to be less stiff than when it had lower Poisson's ratios. Regarding the ratio of deformation to action, the higher the ratio, the less stiff the object was reported as being. It is interesting to note that regardless of the consistency between action and deformation, the same pattern of evaluation was observed.

From these results, the following conclusions can be drawn.

- By manipulating the relationship between the user's action and deformation of a virtual object, we can create a mid-air pseudo-haptic sensation for the user.
- Using the Poisson effect, it is possible to manipulate the perceived stiffness of a virtual object by changing the amount of deformation of the object in accordance with the user's action.
- Even if the user's motion and deformation of the virtual object do not match, it does not affect the impression of the object's softness.

6. The future targeted with this technology

The Innovative Optical and Wireless Network (IOWN) will achieve high-speed, high-capacity communications in 2030. At that time, technology to present a large amount of information to users in a natural

manner will be essential. As described in the IOWN concept document, NTT is aiming for a futuristic user interface "Point of Atmosphere (PoA)" to create a world where people are in harmony with their digital environment without being aware of surrounding devices [5].

The pseudo-haptic technology proposed in this study enhances the sense of realism in the virtual world by extending the experience of real object manipulation to a virtual object so that the virtual object appears to stretch when the user makes a pulling action. This type of object manipulation and impression of material properties in augmented reality will be necessary for future interface design. We hope to bring PoA closer to reality by promoting basic research for the development of not only mid-air pseudo-haptics but also perception-based presentation technology.

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Evaluation of Adaptability to Unfamiliar Environments Using Virtual Reality

Takashi Isezaki and Tomoki Watanabe

Abstract

To prevent accidents when the elderly walk or drive a car, it is important to improve their motor functions, but their cognitive ability to adapt to changes in their environment so that they can move appropriately for their activity is also important. We are conducting research to develop technology for evaluating and improving the ability to adapt to the environment while moving. This article introduces initiatives toward such technologies.

Keywords: VR, cognitive function, manual dexterity

1. Significance of evaluating ability to adapt to the environment while moving

Accidents related to mobility for the elderly, such as falling down and automobile accidents, are societal issues. Falling while walking accounts for a significant proportion of deaths among the elderly. Elderly persons also account for 18.1% of traffic accidents, and the proportion of accidents caused by elderly drivers tends to increase yearly [1].

NTT Service Evolution Laboratories is conducting research on estimating users' mobility function from inertial data and surface electromyogram data [2, 3]. Mobility behaviors, such as walking or driving a car, are considered to be performed based on a general motor control model. This involves a sequence of processes: that of perceiving the state of one's body and the external environment through visual, auditory, and somatic senses; cognitive processing of the perceived information in the brain; sending instructions to the musculoskeletal system; and the mobility processes in which the musculoskeletal system receives the instructions from the brain and muscles contract or relax accordingly. To understand the causes of elderly people falling down while walking or being involved in traffic accidents and prevent such incidents, it is necessary to examine all of these faculties, not just mobility. Cattell subdivided intelligence into two aspects: crystallized intelligence and fluid intelligence [4]. Fluid intelligence is the ability to learn new things or solve problems to adapt to new environments, and is thought to decline with age. Conversely, crystallized intelligence includes the abilities an individual acquires through experience, training, and practice throughout their life and tends to be stable despite the passing of years. When walking or driving a car, one often leaves familiar roads and drives on new and unfamiliar routes or encounters unexpected situations such as pedestrians who suddenly appear. When appropriate mobility behaviors are required in an environment that is changing from minute to minute, fluid intelligence, or the cognitive ability to adapt immediately to unfamiliar or unexpected aspects in the environment, is important. Therefore, evaluating and improving the user's ability to adapt to unfamiliar or unexpected environments while moving are important in preventing accidents related to mobility.

2. Virtual-reality system for evaluating ability to adapt to the environment while moving

To measure users' ability to adapt to their environment requires observation of their behavior in unfamiliar

and unexpected environments, evaluation and analysis of the environment, and their bodily movement in response. Various manufacturers have recently begun selling consumer-oriented virtual reality (VR) systems that anyone can use. VR is able to simulate and reproduce various environments and provide information on those environments and the user's movements in those environments. The concept for this research was to use VR to create environments that are unfamiliar to the user then measure their ability to adapt to those environments by observing their movements and performance in the environments.

To evaluate the ability to adapt to the environment while moving requires analysis of bodily information, including how behaviors differ when the ability to adapt to the environment is strong or weak. The level of dexterity (skill) with the upper limbs (including upper arms, forearms, and hands) is understood to be related to cognitive functions [5]. Considering the ability to adapt to the environment while moving as one of these cognitive functions, our concept was to evaluate this ability by focusing on dexterity in the upper limbs. There are many methods for evaluating dexterity in the upper limbs, but three basic upper-limb mobility functions have been identified related to dexterity, which are spacing, timing, and grading [6]. Spacing is the ability to move the hand in the correct direction, timing is the ability to move the hand by correctly adjusting the timing, and grading is the ability to correctly adjust the effort applied while moving. NTT Service Evolution Laboratories is conducting joint research with Prof. Kensaku Mori and Assoc. Prof. Masahiro Oda of the School of Information Science, Nagoya University, and Prof. Hitoshi Hirata and Designated Assistant Prof. Shintaro Oyama of the Department of Hand Surgery in the School of Medicine, Nagoya University, for implementing a system using VR to evaluate the ability to adapt to the environment while moving that is based on the dexterity of the upper limbs.

For upper limb dexterity, we focused specifically on the task of catching a falling ball. To simulate an environment in which the users were not accustomed to, we conceived three scenarios that would produce differences from behavior in the real world. The first was to change the characteristics of the object (ball). In particular, we examined changes in the acceleration of gravity and the size of the object and created an implementation in which these parameters are variable. The second was to change the characteristics of the environment space. We examined spaces with obstacles that cause the object to bounce and in which the acceleration of the object (ball) changes three dimensionally. We implemented these obstacles and the space so that the range, rebound coefficients, and acceleration settings could be set arbitrarily. The third scenario was to change the motion characteristics of the user. In this case, we set the parameters, i.e., coefficients used to project real-world upper-limb movements onto movements of the avatar in VR space; either exaggerating or attenuating the movements.

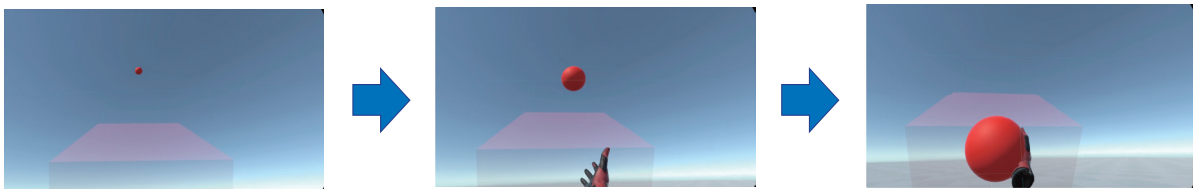
Figure 1 shows images of using a prototype of our VR system. In this task of catching a falling ball from the scenario of changing the characteristics of the environment space, a prescribed range (shown in red) is an obstacle, which bounds the environment in which the ball is falling, simulating changes in the characteristics of the environment. Through multiple trials, the users were able to adapt to this unfamiliar environment and consistently catch the ball. The system measures the user's movement data (from the controller) and their performance while performing the task in the specified environment. A sequence of user operations for one task (Fig. 1(a)) and the user's VR perspective (Fig. 1(b)) are shown. As shown in Fig. 1(a), the user in the real world wears a head-mounted display (HMD) and uses controllers, which are part of the VR system. The video shown on the display in Fig. 1(a) is the VR data that the user receives through the HMD. Video selected from what the user sees in the HMD is shown in Fig. 1(b). The left is a scene with the red ball falling from above, the center shows the ball bouncing off of the obstacle (the red region), and the right shows the ball having been caught by the user.

Figure 2 shows graphs of (a) the cumulative number of successes and (b) reproducibility of the motion when a single user performed multiple trials of the task. Reproducibility of motion is computed as the correlation coefficient for the motion data between trials. It is clear that both the cumulative successes and movement reproducibility increased with the number of trials. By quantifying changes in performance such as success rates and motion reproducibility as trials accumulate, we expect to be able to evaluate the user's ability to adapt to the environment while moving.

3. Future development

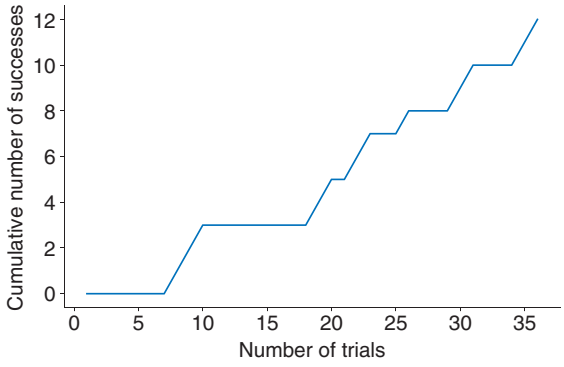
This article introduced a VR system for evaluating the ability to adapt to an environment while moving. It enables movement data and performance measurements

(a) Experimental setup for task of a user trying to catch a falling ball

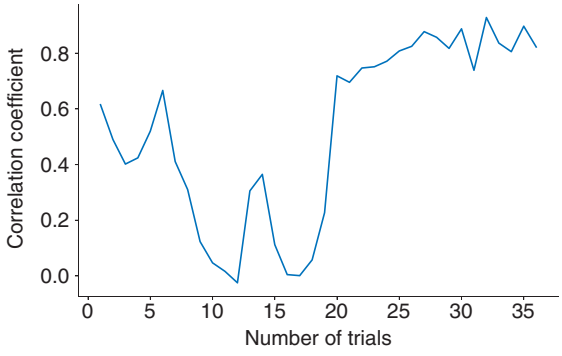


(b) Video from the user's perspective

Fig. 1. Images of a prototype of our VR system.



(a) Change in cumulative successes



(b) Change in reproducibility of motion

Fig. 2. An analysis example from a user.

to be collected during the process of adapting to changes in the environment. We intend to continue studying methods for evaluating the cognitive function of the ability to adapt to the environment while moving, on the basis of data from participants with various attributes, using measured motion and performance data. We also intend to continue updating the tasks and configurations in our prototype VR system.

We plan to investigate the significance of this evaluation of adaptability in the real world, beyond falling or traffic accidents, to issues with a wide range of cognitive functions, such as forgetfulness. We will also investigate how this system can be used to improve adaptability to the environment while moving.

During the current novel coronavirus pandemic, we frequently encounter situations in which we cannot go out for a walk or other exercises. The need for technologies for training our bodies while at home is higher than ever before. Many devices are being brought to market that are designed to improve mobility-related functions, such as muscle mass, and we expect that training cognitive functions using devices/systems, such as that introduced in this article, will also become more common. We will contribute to extending the healthy lives of everyone by creating

technologies to evaluate and improve cognitive function in various ways and implement them in peoples' homes as evaluation and training systems.

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Increasing Capacity of a Strictly Non-blocking Clos Network Composed of Optical Switches

Toru Mano, Takeru Inoue, Kimihiro Mizutani, and Osamu Akashi

Abstract

Clos networks are widely used due to their non-blocking property. However, in strictly non-blocking Clos networks composed of ordinary optical switches (switches with equal numbers of input/output ports), we find that a substantial number of ports can remain unused, which decreases their efficiency. This inefficiency comes from the implicit restriction that the two *sides* of switches have distinct roles, i.e., ports on one side are connected to endpoints (terminals) while those on the other side are linked to switches. Removing this restriction provides greater freedom in constructing a network and can increase capacity without losing the strictly non-blocking property. We propose a new strictly non-blocking network and provide several theorems that address network capacity. Numerical experiments show that the proposed network has up to 30% more capacity compared with a strictly non-blocking Clos network.

Keywords: non-blocking switching networks, Clos network, network design

1. Introduction

Constructing *non-blocking* switching networks [1], where connections can be established between any pair of idle ports, remains a vital issue in the field of network design. Such networks have been applied in many areas such as telephone networks [2], asynchronous transfer mode networks [3], optical switching with wavelength-division multiplexing technologies [4], and time-division packet switching [5]. A rich body of literature has been produced on non-blocking networks with the goal of constructing larger-capacity networks [6, 7]. Clos networks [2] are classic networks, and their capacity has been extensively analyzed [8], e.g., 10,000 connections can be accommodated using 59 2000-port switches arranged in a three-stage network.

To the best of our knowledge, studies on non-blocking networks made the implicit restriction that switches have two facing *sides* with several ports, and only one side can be used to connect to endpoints [9, 10]. For example, in Fig. 2, for switches in the input layer, the left side is connected to endpoints (*t*'s) while the right side is linked to switches. This restriction makes it easy to understand the network, but it might decrease the efficiency of a Clos network if it consists of ordinary *square switches* (switches with equal numbers of input/output ports) [11, 12]. As discussed in Section 3, a substantial number of ports has to remain unused in a Clos network, e.g., in Fig. 2, if unused (black) ports are connected, the capacity would not increase or the network would lose its non-blocking property.

We focus on a non-blocking switching network with greater capacity than the Clos equivalents. To increase capacity, we remove the above implicit restriction while still using square switches, which have equal numbers of input/output ports, as used in previous studies [9, 10]. To the best of our knowledge, this is the first study on maximizing the capacity of non-blocking networks that use square switches without the above restriction. Among the several

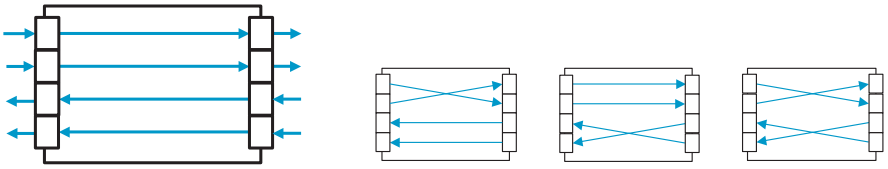

Fig. 1. All four possible configurations in a square switch of $N = 4$.

known non-blocking properties [1], we investigated non-blocking networks in the *strict sense* (any idle port can be connected independent of current connections) with the most fundamental form of space-division multiplexing*1. Note that we focus on networks with only a single intermediate layer to mitigate signal attenuation. Since our focus is on the strict non-blocking property, routing issues are not discussed.

The contributions of this article are summarized as follows.

- Section 3 reveals that a substantial number of ports can remain unused in Clos networks.
- Section 4.1 proposes a strictly non-blocking network that is based on a Clos network.
- Section 4.2 proves that the proposed network has equal or larger capacity than a Clos network.
- Numerical evaluations with reasonable parameters showed that the proposed network has up to about 30% larger capacity than a Clos network (Section 5).

2. Preliminaries

2.1 Problem statement

The basic switching component is represented as a *square switch*, as illustrated in **Fig. 1**. A square switch has two sides, and each side has N ports. Although input and output ports can coexist on the same side, we are only allowed to connect an input port on one side with an output port on the other side. We assume that all switches have equal N. The size of a square switch is defined as N.

A *switching network* is defined as a set of switches connected by directional links (optical fibers), and the network is connected to *endpoints*, as illustrated in **Fig. 2**. Ports connected to an endpoint are called *external* ports, while the other ports are called *internal* ports. Ports without links are called *unused* ports. Since links have a direction, all external/internal ports and endpoints are classified as either *transmitting* or *receiving*. Every transmitting port/endpoint is allowed to connect only with a receiving one. We consider switching networks with a single layer of intermediate switches (intermediate switches are those without external ports) such as one-sided two-stage (Fig. 2 and **Fig. 3**) and two-sided three-stage (**Fig. 4**) networks.

Connection requests are classified into two categories: creation and termination. A creation request, specified by a pair of idle endpoints, triggers the establishment of a path between the endpoints. In Fig. 2, two endpoints t_1^1 and r_2^1 are specified, and the thick gray line represents the path established between them. A termination request, which specifies an existing connection, releases the corresponding path. Note that the request sequence is *unknown* in advance.

Strictly non-blocking networks are designed to accept any request sequence without requiring the rearrangement of existing paths. Moreover, paths used to satisfy creation requests should be chosen arbitrarily. Thus, the path-selection algorithm is outside the scope of this article.

Our problem, the *connection maximization problem*, is defined as follows. Given the number of switches, construct a strictly non-blocking network that has the maximum number of connections. This maximum number of connections is the capacity of the network. In Fig. 2, given seven switches, eight connections can be established between the eight transmitting endpoints and eight receiving endpoints.

2.2 Current approach: Clos networks

This subsection reviews current non-blocking networks, i.e., their connection schemes, non-blocking conditions, and formulations of the connection maximization problem. We explain two current Clos networks: *unfolded Clos* [2, 6, 9] and *folded Clos* [7, 10]. Note that an unfolded Clos network is usually called just a Clos network, but to eliminate the ambiguity

*1 Extension to time-division, wavelength-division, and code-division multiplexing [7] is for our future work.

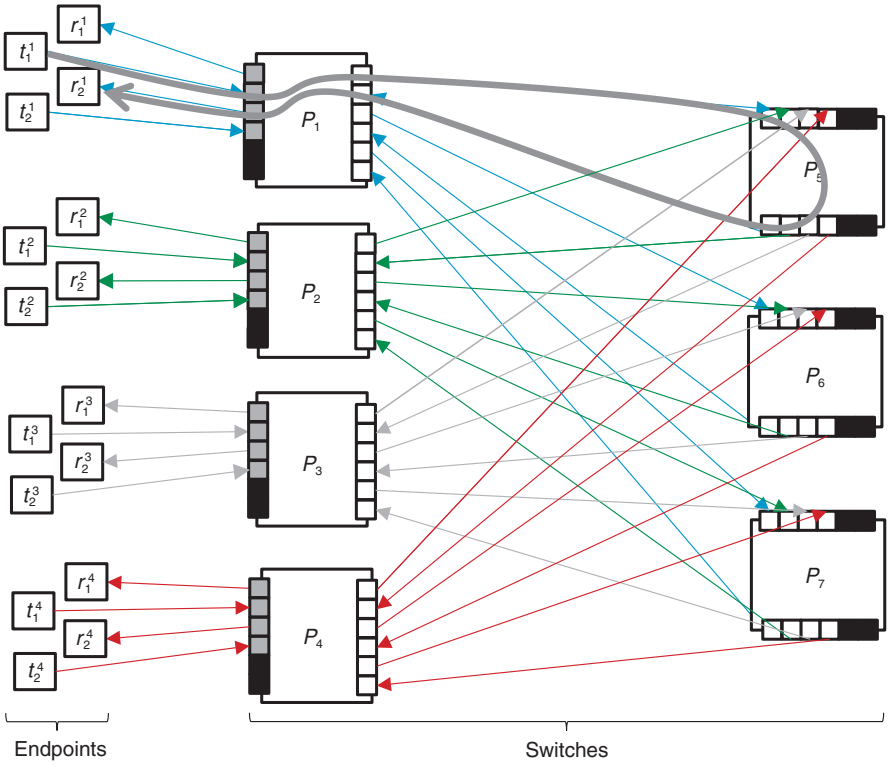

Fig. 2. An example of strictly non-blocking switching network ($N = 6$). External switch ports are gray, internal switch ports are white, and unused ports are black.

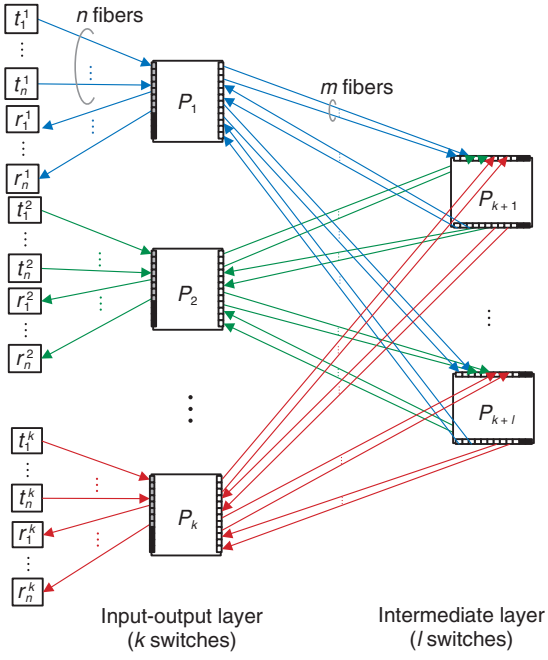

Fig. 3. A folded Clos network consisting of $k + l$ switches. This network offers up to $n \cdot k$ connections.

between folded and unfolded, we explicitly call it an unfolded Clos network. The disadvantages of these networks are analyzed in Section 3. These networks are similar, but they have different capacities, as discussed in Section 5.

As explained in the Introduction, these networks have an implicit restriction; ports on one side are either all external or all internal; mixing is not permitted.

2.2.1 Folded Clos networks

Figure 3 illustrates a folded Clos network [7, 10]. A folded Clos network has $k > 2$ switches in the input-output layer and l switches in the intermediate layer. The case of $k \leq 2$ is ignored because it can support at most N connections, and a single switch is sufficient. The right side of each switch in the input-output layer is connected to each side of the switches in the intermediate layer with m fibers. The left side of each switch, P_i, in the input-output layer is connected to n transmitting endpoints, $\{t_j^i\} j = 1,\ldots, n$, and n receiving endpoints, $\{r_j^i\} j = 1,\ldots, n$. Hence, a folded Clos network can serve $n \cdot k$ connections in total. In Fig. 3, substituting 4, 3, 1, 2 with k, l, m, n, respectively, yields the network in Fig. 2.

The network is strictly non-blocking if and only if [7]

$$2\left\lfloor \frac{n-1}{m} \right\rfloor + 1 \leq 1. \tag{1}$$

Therefore, as illustrated in Fig. 2, if we increase the number of external ports, n, to 3 from 2, i.e., 3 transmitting external ports and 3 receiving ones, then the network loses its strictly non-blocking property.

In folded Clos networks that use at most a switches with N ports, the maximum number of connections, i.e., the capacity $f_C(a; N)$ can be obtained by solving the following problem over positive integer variables $k(> 2)$, l, m, $n \in \mathbb{N}$.

$$\begin{aligned} \max \quad & n \cdot k && (2)\\ \text{s.t.} \quad & n \leq \lfloor N/2 \rfloor && (3)\\ & m \cdot l \leq \lfloor N/2 \rfloor && (4)\\ & m \cdot k \leq N && (5)\\ & 2\left\lfloor \frac{n-1}{m} \right\rfloor + 1 \leq l && (6)\\ & k + l \leq a. && (7) \end{aligned}$$

Objective (2) represents the number of connections in a folded Clos network, and Constraints (3), (4), and (5) infer that each side of the switch has enough ports for fiber provision. Constraint (6) guarantees the non-blocking property, and Constraint (7) restricts the number of switches used. We say the connection parameters (k, l, m, n) are *feasible* for a folded Clos network if they satisfy Constraints (3), (4), (5), and (6).

2.2.2 Unfolded Clos networks

Figure 4 illustrates an unfolded Clos network [2, 6, 9]. Its connection scheme is similar to that of folded Clos networks. We consider only $k > 1$ for the same reason given for folded Clos networks.

This network is strictly non-blocking if and only if [6]

$$2\left\lfloor \frac{n-1}{m} \right\rfloor + 1 \leq l. \tag{8}$$

As with a folded Clos network, the maximum number of connections, i.e., the capacity $f_U(a; N)$, can be obtained by solving the following problem over positive integer variables $k(> 1)$, l, m, $n \in \mathbb{N}$.

$$\begin{aligned} \max \quad & n \cdot k && (9)\\ \text{s.t.} \quad & n \leq N && (10)\\ & m \cdot l \leq N && (11)\\ & m \cdot k \leq N && (12)\\ & 2\left\lfloor \frac{n-1}{m} \right\rfloor + 1 \leq l && (13)\\ & 2k + l \leq a. && (14) \end{aligned}$$

3. Disadvantages of using Clos networks

This section explains the disadvantages of Clos networks. Moderately sized strictly non-blocking folded Clos and unfolded Clos networks must have relatively large numbers of unused ports.

Proposition 1. Let s be an integer greater than 1. A strictly non-blocking folded Clos network that can serve at least sN connections has at least $\frac{1}{2}\left(1-\frac{1}{s}\right)N$ unused ports on the left side of the input-output switch. That is, if connection parameters (k, l, m, n) are feasible for this network and satisfy $nk \geq sN$, then $N - 2n \geq \frac{1}{2}\left(1-\frac{1}{s}\right)N$.

Proof. Let (k, l, m, n) be feasible connection parameters with $nk \geq sN$. We have $k \geq 2s$ because of Constraint (3) and condition $nk \geq sN$. Let q be an integer such that $q = \left\lfloor \frac{n-1}{m} \right\rfloor$, then we have $n \leq (q + 1)m$ and $2q + 1 \leq l$ from Constraint (6). Together with Constraints (4) and (5), we have $2n \leq (l + 1)m \leq 2n \leq (l + 1)m \leq \frac{N}{2} + \frac{N}{2s} = \frac{1}{2}\left(1 + \frac{1}{s}\right)N$.

Proposition 2. Let s be an integer greater than 1. A strictly non-blocking unfolded Clos network that can serve at least sN connections has at least $\frac{1}{2}\left(1-\frac{1}{s}\right)N$ unused ports on the left/right side of the input/output switch. That is, if connection parameters (k, l, m, n)

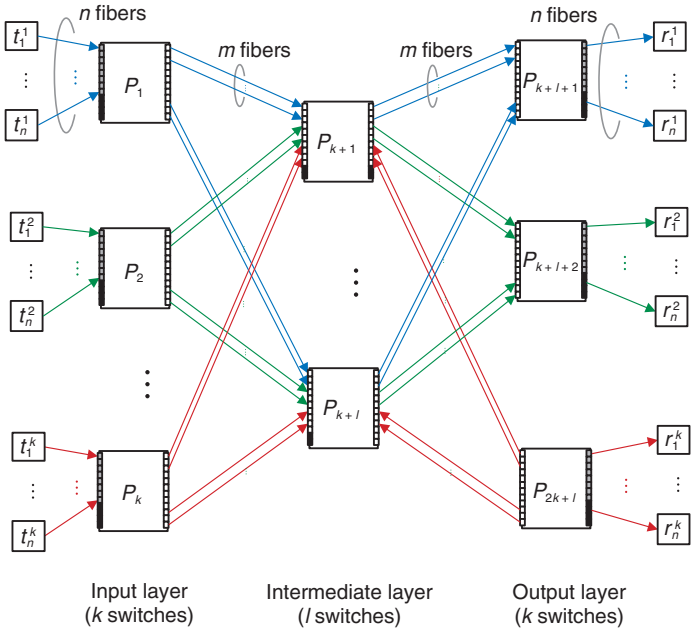

Fig. 4. An unfolded Clos network consisting of $2k + l$ switches. This network offers up to $n \cdot k$ connections.

are feasible for this network and satisfy $nk \geq sN$, then $N - n \geq \frac{1}{2}\left(1 - \frac{1}{2}\right) N$.

Proof. Let (k, l, m, n) be feasible connection parameters with $nk \geq sN$. We have $k \geq s$ because of Constraint (10) and condition $nk \geq sN$. Let q be an integer such that $q = \left\lfloor \frac{n-1}{m} \right\rfloor$, then we have $n \leq (q + 1)m$ and have $2q + 1 \leq l$ from Constraint (6). Together with Constraints (11) and (12), we have $n \leq \frac{l+1}{2} m \leq \frac{N}{2} + \frac{N}{2s}$ $= \frac{1}{2}\left(1 + \frac{1}{s}\right) N$.

The above propositions show that the capacity of folded Clos or unfolded Clos networks increases and more ports are unused: the number approaches $\frac{N}{2}$ asymptotically. This was also observed through the numerical evaluation discussed in Section 5.

4. Proposed network

In this section, we explain the proposed network that is based on folded Clos networks. First, we explain the proposed network and its non-blocking condition. We then compare its capacity with that of Clos networks from the theoretical viewpoint.

4.1 Proposed network and its non-blocking condition

Figure 5 illustrates the proposed network. Both sides of the input-output layer are connected to endpoints. At the left side of each switch in the input-output layer, n ports are connected to receiving endpoints, while every m port is connected to the down

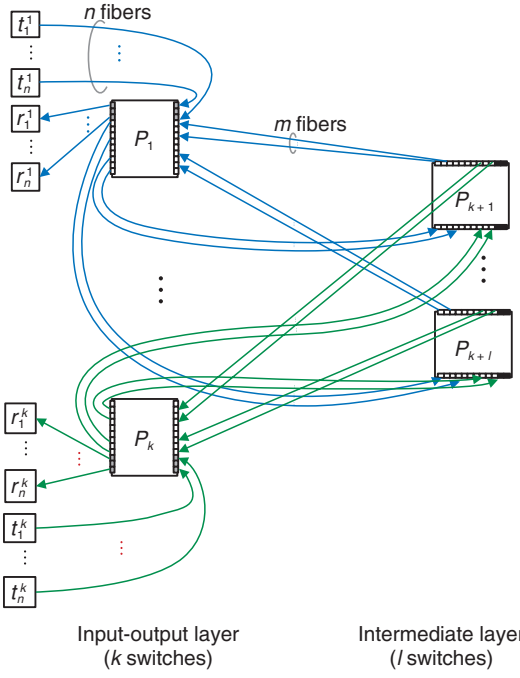

Fig. 5. The proposed switching network consisting of $k + l$ switches. This network offers up to $n \cdot k$ connections.

side of a switch in the intermediate layer. The right side mirrors this configuration. The proposed network offers $n \cdot k$ connections in total. We consider only $k > 2$ as per a folded Clos network. We confirmed that the construction of the proposed network is feasible on commercially available optical switches.

The strictly non-blocking condition, Condition (1), does not change, and the proof is almost the same as for a Clos network [2, 6] (the proof is given at the end of this subsection).

Proposition 3. The proposed network is strictly non-blocking if and only if

$$2\left\lfloor \frac{n-1}{m} \right\rfloor + 1 \leq l. \tag{15}$$

The maximum number of connections, i.e., the capacity $f_P(a; N)$, can be obtained by solving the following problem on positive integer variables $k(>2)$, l, m, $n \in \mathbb{N}$.

$$\begin{aligned} \max \quad & n \cdot k && (16)\\ \text{s.t.} \quad & n + m \cdot l \leq N && (17)\\ & m \cdot k \leq N && (18)\\ & 2\left\lfloor \frac{n-1}{m} \right\rfloor + 1 \leq l && (19)\\ & k + l \leq a. && (20) \end{aligned}$$

Compared to a folded Clos network, the constraints related to input-output square switch size, i.e., Constraints (3) and (4), are replaced with Constraint (17). The other constraints are the same.

As discussed in Section 5, the proposed network has less unused ports compared with current networks because the proposed network does not have the implicit restriction, that is, a single side in the proposed network can have both external and internal ports.

Finally, we give a proof of Proposition 3.

Proof of Proposition 3. First, we discuss sufficiency. Without loss of generality, we can assume that a connection-creation request (t_1^1, r_1^2) has arrived. Because P_1 uses at most $n-1$ fibers connected to transmitting endpoints, at most $n-1$ fibers that go to intermediate switches from P_1 are used. With the same argument, at most $n-1$ fibers that come to P_2 from intermediate switches are used. Hence, at most $\left\lfloor \frac{n-1}{m} \right\rfloor$ intermediate switches run out of available fibers that come from P_1, and at most $\left\lfloor \frac{n-1}{m} \right\rfloor$ intermediate switches run out of available fibers that go to P_2. Thus, if we have $2\left\lfloor \frac{n-1}{m} \right\rfloor + 1$ intermediate switches, there exists at least one intermediate switch that has an available fiber coming from P_1 while another one goes to P_2. By using this intermediate switch, we can establish the connection.

Next, we discuss necessity. Suppose l is $2\left\lfloor \frac{n-1}{m} \right\rfloor$, and connection-creation requests $\{(t_i^1, r_i^2)\} i = 1, \ldots, n-1$ and $\{(t_i^2, r_i^3)\} i = 1, \ldots, n-1$ have arrived; the former requests $\{(t_i^1, r_i^2)\}$ use the first $l/2$ intermediate switches, and latter requests $\{(t_i^2, r_i^3)\}$ use the last $l/2$ intermediate switches. Note that a strictly non-blocking network has to establish a connection between idle ports regardless of the past path selection. However, connection-creation request (t_n^1, r_n^3) cannot occur because the first $l/2$ intermediate switches do not have any available fiber coming from P_1 and the last $l/2$ intermediate switches do not have any available fiber going to P_3.

4.2 Capacity comparison

This subsection compares capacity from a theoretical viewpoint. We show that the proposed network has equal or larger capacity than a folded Clos network (Theorem 1). With regard to an unfolded Clos network, we give only a sufficient condition for the proposed network to have equal or larger capacity (Theorem 2). Due to the complexity of the discrete nature of integers, it is intractable to analyze the remaining case, i.e., the case that Theorem 2 does not cover. To compare the remaining case, we conducted a numerical evaluation, as discussed in Section 5.

First, we prove that the capacity of the proposed network $f_P(a; N)$ is greater than or equal to that of a folded Clos network $f_C(a; N)$.

Theorem 1. The proposed network has equal or larger capacity than a folded Clos network. That is, we have

$$f_C(a; N) \leq f_P(a; N) \tag{21}$$

when there is a feasible solution for a folded Clos network.

Proof. Suppose that the connection parameters (k, l, m, n) are feasible for a folded Clos network. That is, (k, l, m, n) satisfy Constraints (3), (4), (5), (6), and (7). Then, it is sufficient to show that (k, l, m, n) are also feasible for the proposed network. The only difference between the proposed and folded Clos networks is that a folded Clos network has Constraints (3) and (4), whereas the proposed network has Constraint (17). We have $\left\lfloor \frac{N}{2} \right\rfloor + \left\lfloor \frac{N}{2} \right\rfloor \leq N$. Since Constraints (3) and (4) infer another Constraint (17), (k, l, m, n) are also feasible for the proposed network.

Next, we give a sufficient condition for the

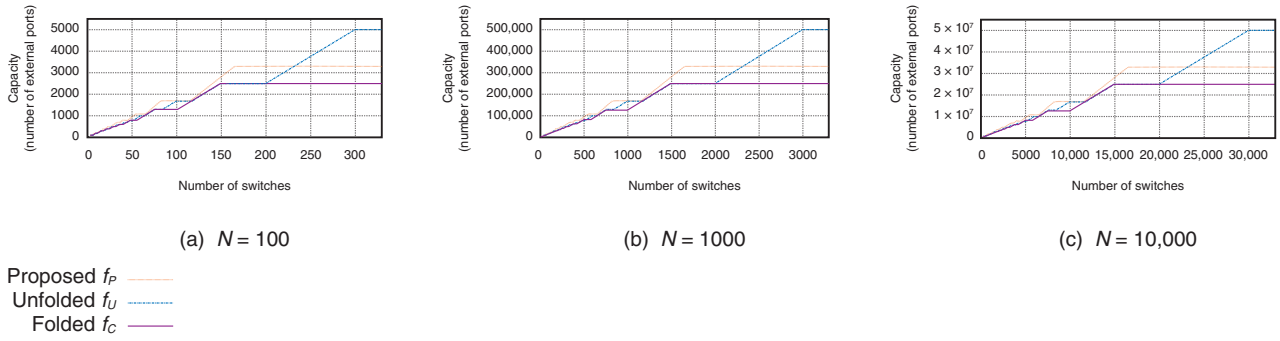

Fig. 6. The capacity and number of switches used. We examined three square switch sizes N = 100 (a), 1000 (b), and 10,000 (c). All three cases generated almost identical plots.

proposed network to have equal or larger capacity to an unfolded Clos network.

Theorem 2. If one of the optimal configurations of an unfolded Clos network has even m, then the proposed network has equal or larger capacity, i.e., $f_U(a; N) \leq f_P(a; N)$, where m is the number of connections between the input/output switches and intermediate switches.

To prove Theorem 2, we use the following proposition and lemma. First, we give a proof of the lemma, then provide a proof of the proposition, and finally prove Theorem 2.

Proposition 4. Let (k, l, m, n) be feasible for an unfolded Clos network and m be an even integer. There exist feasible parameters (k', l', m', n') for the folded Clos network such that $nk \leq n'k'$ and $2k + l \geq k' + l'$.

Lemma 1. Let (k, l, m, n) be feasible for an unfolded Clos network, m be an even integer, and n be an odd integer. Parameters $(k, l, m, n+1)$ are also feasible for the unfolded Clos network.

Proof of Lemma 1. Let q be an integer such that $q = \left\lfloor \frac{n-1}{m} \right\rfloor$. It is sufficient to show $n+1 \leq N$ and $\left\lfloor \frac{n}{m} \right\rfloor = q$. Since n is odd and m is even, we have $qm + 1 \leq n \leq m(q+1) - 1$. This inequality gives us $\left\lfloor \frac{n}{m} \right\rfloor = q$. In addition, since Constraint (11) is satisfied, we have $n+1 \leq m(q+1) \leq m(2q+1) \leq ml \leq N$.

Proof of Proposition 4. Due to Lemma 1, we can assume that n is also even. Hence, it is sufficient to show that $(k', l', m', n') = \left(2k, 2\left\lfloor \frac{n-1}{m} \right\rfloor + 1, \left\lfloor \frac{m}{2} \right\rfloor, \left\lfloor \frac{n}{2} \right\rfloor\right)$ are also feasible for the folded Clos network. That is, we show that (k', l', m', n') satisfy Constraints (3), (4), (5), and (6). Since m and n are even, Constraints (3), (4), and (5) are satisfied. Let us consider the remaining constraint, Constraint (6). Let q be an integer such that $q = \left\lfloor \frac{n-1}{m} \right\rfloor$, then by using integer $r \in \{0, 1, ..., m-1\}$, n can be represented as $n = mq + r + 1$. By dividing by 2 and subtracting 1, we have $n' - 1 = m'q + (r+1)/2 - 1$. Since m and n are even, the residue $(r+1)/2 - 1$ is one of $\{0, 1, ..., m'-1\}$. Hence, we have $2\left\lfloor \frac{(n'-1)}{m'} \right\rfloor + 1 = 2\left\lfloor \frac{n-1}{m} \right\rfloor + 1 = l'$.

Proof of Theorem 2. We prove the theorem by contradiction using Theorem 1 and Proposition 4. Suppose that there exists a configuration of an unfolded Clos network with even m that has a larger capacity than the proposed network. Then, by Proposition 4, we can convert this unfolded Clos network into a folded Clos network without losing capacity. Hence, the converted folded Clos network has larger capacity than the proposed network. However, this contradicts Theorem 1.

5. Numerical evaluation

This section numerically compares the proposed network with folded and unfolded Clos networks[*2]. We now show that the proposed network has improved capacity.

First, we show that switch size slightly affects the results. **Figure 6** shows the capacity (y-axis) and number of switches used (x-axis). We plot the results for the folded Clos, unfolded Clos, and proposed networks, that is, $f_C(a; N)$, $f_U(a; N)$, and $f_P(a; N)$. We used three switch sizes, N = 100 (Fig. 6(a)), 1000 (Fig. 6(b)), and 10,000 (Fig. 6(c)). All three cases generated almost identical plots. We confirmed that

*2 The capacity of an unfolded Clos network matches that of a folded Clos network. For example, let the switch size be N =100 and the number of switches be one of {8, 9, ..., 12}. Then the unfolded Clos network has larger capacity for a = 8, 12, and the folded Clos network has larger capacity for a = 9, 10, 11.

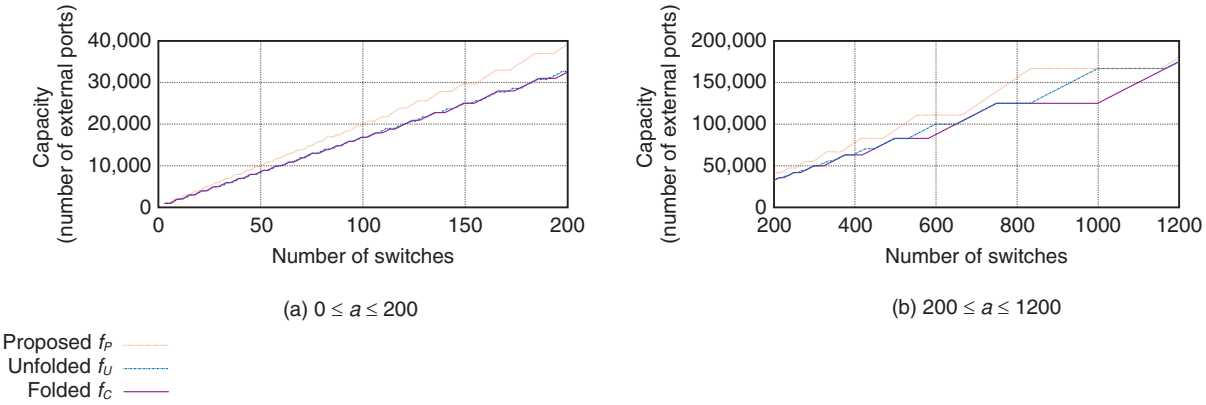

Fig. 7. The capacity and number of switches used for smaller *a*. These plots were obtained by enlarging Fig. 6(b).

other switch sizes, $N \in \{200, 300, ..., 900\} \cup \{2000, 3000, ..., 9000\}$, generated almost identical plots. These results imply that switch size slightly affects capacity comparison. Note that, in the folded Clos, unfolded Clos, and proposed networks, the line became flat when a exceeded around $3/2N$, $3N$, and $5/3N$, respectively. The reason is that capacity does not increase even if we add more available switches since we run out of internal ports that the switches can use to connect with each other. One way to evade this situation is adding another intermediate layer. However, as explained in Section 2.1, we considered networks with a single intermediate layer. Extension to multistage networks is for future work.

Next, we compared the capacity of the proposed network with folded Clos and unfolded Clos networks. We investigated plots for a certain switch size since, as we saw above, the switch size slightly affects the plots. We chose N of 1000. **Figure 7** is an enlargement of Fig. 6(b), i.e., replots the curves with smaller ranges of a, since it is difficult to tell the difference among the three lines from Fig. 6(b) when a is relatively small. Figures 7(a) and 7(b) illustrate the plots for $0 \le a \le 200$ and for $200 \le a \le 1200$, respectively. These three figures show that the proposed network has equal or larger capacity than the folded Clos network and that the proposed network has equal or larger capacity than the unfolded Clos network if $a \le 2.3N$. In fact, the proposed network has up to about 30% more capacity. For example, when the number of available switches a is 833, the capacity of a folded Clos network is 125,000 with $(k, l, m, n) = (500, 249, 2, 250)$, and that of an unfolded Clos network is 125,250 with $(k, l, m, n) = (250, 333, 3, 501)$, whereas that of the proposed network is 167,000 with $(k, l, m, n) = (500, 333, 2, 334)$. We also compared capacity using other switch sizes, $N \in \{200, 300, ..., 900\} \cup \{2000, 3000, ..., 9000\}$ and confirmed that the proposed network has equal or larger capacity than an unfolded Clos network if $a \le 2.3N$.

Finally, we compared the number of unused ports on the left side of the input switch; those of a folded Clos, unfolded Clos, proposed networks are $N–2n$, $N–n$, $N–n–ml$, respectively. **Figure 8** shows the number of unused ports when $N = 1000$. In the folded Clos and unfolded Clos networks, almost half the ports remained unused, whereas, in the proposed network, the number of unused ports was less than 10 in more than 90% of $a \le 3000$. The largest number of unused ports was 134 when $a = 1155$. At this point ($a = 1155$), m of the optimal connection parameters decreased to 1 from 2, and this change made some ports unused. We also compared the number of unused ports using other switch sizes and obtained similar results.

6. Related work

A Clos network is one of the most commonly used non-blocking networks [1, 2, 6]. Many studies have examined non-blocking properties under various switching environments. There are four non-blocking properties; strictly [2], wide-sense [6], re-arrangeably [1], and re-packably [7]. The wide-sense property allows us to select which path is used to establish a new connection. Under the strict property, the path is arbitrarily chosen. The latter two enable us to rearrange existing paths to establish connections. We focused on strictly non-blocking networks because wide-sense non-blocking fails to significantly

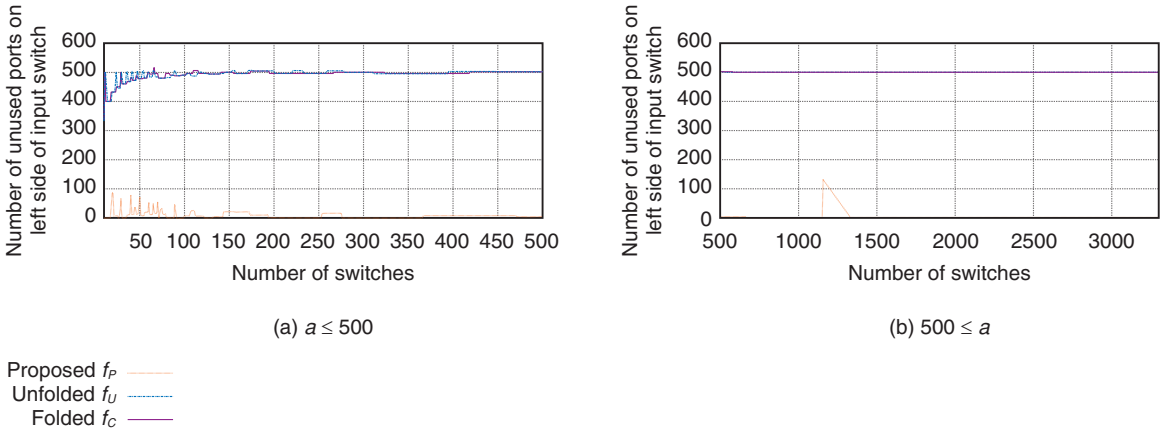

Fig. 8. The number of unused ports on the left side of the input switch and number of switches used when $N = 1000$.

increase capacity if at all [6], and the latter two types require the movement of existing connections, which triggers network outages during path reconfiguration.

7. Conclusion

This article proposed a non-blocking network composed of square switches such as optical switches and confirmed that it has a larger capacity than Clos networks. Our network has up to about 30% more capacity under reasonable parameters. Future work includes investigating routing algorithms on our network and extensions to multiple intermediate layers.

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Recent Standardization Activities in ITU-T on Single-mode Optical Fiber and Space Division Multiplexing Technologies

Taiji Sakamoto, Kazuhide Nakajima, and Noriyuki Araki

Abstract

Optical fiber standards have been discussed in the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T). Various standards (Recommendations) have been developed based on discussions at Study Group 15 and are revised according to the progress in the optical fiber telecommunication system. In this article, recent standardization activities in ITU-T on single-mode optical fiber (SMF) are described. Also, recent discussion toward standardizing space division multiplexing technologies, which are promising for overcoming the capacity limit of SMF, is introduced.

Keywords: single-mode optical fiber, space division multiplexing, ITU-T SG15

1. Introduction

The International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) has developed many standards (Recommendations) to specify telecommunication system requirements, functions, and measurement methods to ensure the interoperability and quality of network services. Development of optical fiber standards is important, particularly for telecom operators, since transmission lines can consist of optical fibers provided from multiple vendors. Therefore, standardization on transmission and geometrical characteristics of optical fibers are mandatory to ensure the interoperability of the telecommunication system. **Table 1** shows the list of ITU-T Recommendations related to optical fibers. They are being developed under the responsibility of Study Group 15 (SG15) [1] Working Party 2 (WP2) Question 5. There are six types of Recommendations regarding single-mode optical fiber (SMF) (G.652–G.657). Question 5 has recently been discussing the revision of existing fiber Recommendations in accordance with the progress in optical fiber transmission technologies. Recommendations G.650.1–650.3, which are standard test methods for optical fibers, are revised in line with the revision of the fiber Recommendations. The G series Supplements are the supplemental documents that provide beneficial information for Recommendation users. The International Electrotechnical Commission (IEC) also has documents for optical fiber standards to describe fiber-product specifications and has developed them in conjunction with the revision of Recommendations in ITU-T.

2. Recent activities on SMF Recommendations

The Recommendations shown in red in Table 1 are those being actively discussed. The G.652 fiber is used worldwide and recognized as “standard SMF.” The G.657 fiber has optical characteristics compatible with those of G.652 fiber but has improved bending loss. These two fibers support transmission over the O–L band* (1260–1625 nm) and used for various applications such as access, metro, and core networks. Recommendation G.654 is for a fiber supporting

Table 1. List of optical fiber Recommendation series.

Category	Document No.	Title
Fiber	G.651.1	50/125 μm multimode graded index optical fibre cable
	G.652	Single-mode optical fibre and cable
	G.653	Dispersion-shifted single-mode optical fibre and cable
	G.654	Cut-off shifted single-mode optical fiber and cable
	G.655	Non-zero dispersion-shifted single-mode optical fiber and cable
	G.656	Fibre and cable with non-zero dispersion for wideband optical transport
	G.657	Bending-loss insensitive single-mode optical fibre and cable
Test method	G.650.1	Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable
	G.650.2	Definitions and test methods for statistical and nonlinear related attributes of single-mode fibre and cable
	G.650.3	Test methods for installed single-mode optical fibre cable link
Supplement	G.Sup.40	Optical fibre and cable Recommendations and standards guideline
	G.Sup.47	General aspects of optical fibres and cables
	G.Sup.59	Guidance on optical fibre and cable reliability

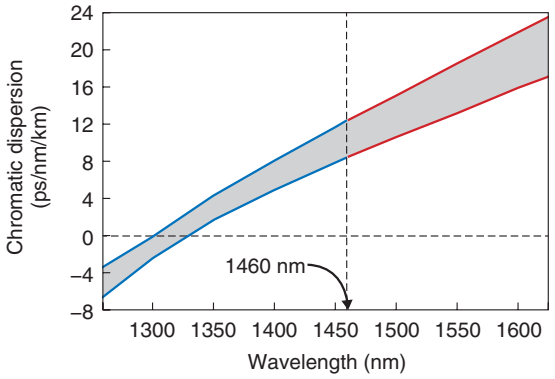
C–L-band* transmission and mainly used for submarine long-haul transmission systems. The revision of these Recommendations are active topics in ITU-T due to the capacity growth in terrestrial and submarine optical fiber networks. In the next section, recent activities for revising these SMF Recommendations are introduced.

2.1 Revision of Recommendations G.652/G.657

In this section, recent revisions to Recommendations G.652 and G.657 are introduced. ITU-T fiber Recommendation specifies, for example, fiber attenuation, mode field diameter (MFD), chromatic dispersion, or bending loss characteristics for satisfying the transmission-system requirements and for ensuring interoperability. The demand for specifying more detailed specifications has increased owing to the increase in the bitrate of transmission systems. Particularly, the wavelength properties of each parameter are becoming important because wavelength division multiplexing (WDM) transmission is an indispensable technology toward ultrahigh capacity transmission. From this background, ITU-T revised Recommendation G.652 in which the detailed wavelength property of chromatic dispersion for G.652.D fiber is specified. The revised specifications are shown in **Fig. 1**. Figure 1(a) shows the previous chromatic dispersion specifications in which the range of the zero dispersion wavelength λ_0 range and maximum dispersion slope at λ_0 are specified. The revised specifications for chromatic dispersion are now described in the latest Recommendation, i.e., G.652, which specifies the maximum and minimum dispersion values

Parameter	Value
Zero dispersion wavelength λ_0	1300–1324 nm
Dispersion slope at λ_0 S_0	< 0.092 ps/nm^2 × km

(a) Previous specifications



(b) Revised specifications

Fig. 1. Chromatic dispersion specifications for G.652.D fiber.

over the wavelength range of the O–L band, as illustrated in Fig. 1(b). The maximum or minimum dispersion boundary for 1260–1460 or 1460–1625 nm is

* O-band (original band: 1260–1360 nm), C-band (conventional band: 1530–1565 nm), and L-band (long-wavelength band: 1565–1625 nm).

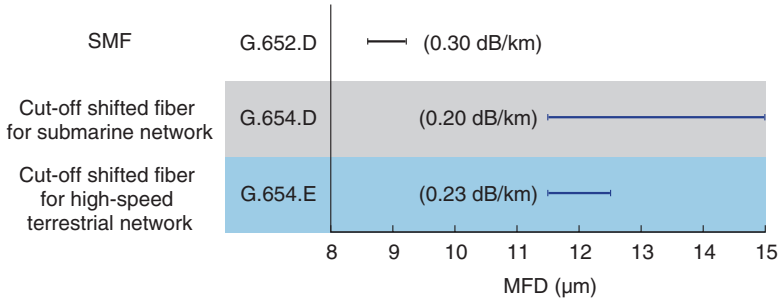


Fig. 2. Comparison of attenuation coefficient and MFD for G.652.D and G.654 fibers.

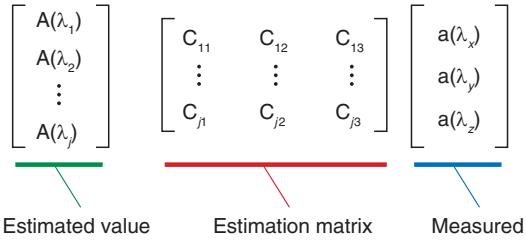
specified using an appropriate fitting function. This revision provides the full O–L-band chromatic dispersion characteristics of G.652.D fiber and helps system operators design the detail system configuration and requirements for future high-speed transmission systems. Since G.657.A fiber has compliant transmission, except for having low bending loss, the same chromatic dispersion specification was introduced in Recommendation G.657.

2.2 Revision of Recommendation G.654

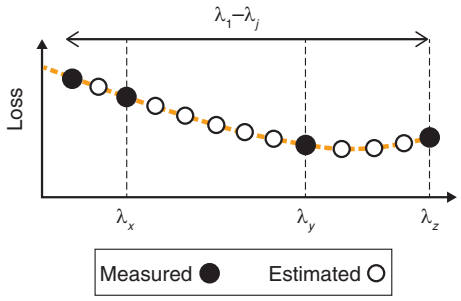
Recommendation G.654 has been developed for use mainly in submarine networks. The features of G.654 fiber are low attenuation coefficient and large MFD compared with those of G.652 fiber, and transmission over low-loss transmission window, i.e., the C–L band, to support long-distance transmission systems. **Figure 2** summarizes the specified fiber attenuation coefficients and MFDs for G.654 sub-categories. The loss attenuation and MFD for G.654 fiber are larger than those for G.652.D fiber. These characteristics are effective for improving signal quality (e.g. signal-to-noise ratio) by reducing the total span attenuation between repeaters or fiber nonlinearity-induced noise. The G.654.D fiber has the largest MFD and was developed for use in long-distance submarine networks. Although Recommendation G.654 was basically developed for submarine use, low loss and large MFD are also being required owing to the increase in the capacity and bitrate in terrestrial networks. The G.654E sub-category was established in 2016, which was for high-speed terrestrial core networks. The G.654.E fiber supports more than 100-Gbit/s-capacity transmission with a lower attenuation coefficient than that for G.652.D fiber and narrower MFD specification range than that for the other G.654 fibers by taking into account multi-vender fiber connections and compatible bending loss to ensure the applicability of the cable structure used in terrestrial networks.

2.3 Revision of Recommendation G.650.1

Recommendation G.650.1 specifies the test methods for optical fiber parameters such as attenuation coefficient and cut-off wavelength. In 2020, Recommendation G.650.1 was revised owing to the recent revisions of the fiber Recommendations in which the attenuation coefficient is specified by the maximum value at a specific wavelength or wavelength range. As fiber attenuation has wavelength dependency, it is important to know the loss spectrum to design a WDM transmission system. To support this requirement, Recommendation G.650.1 describes a method of estimating the attenuation spectrum from measured attenuation values at specific wavelengths. **Figure 3** shows a schematic diagram of this method, where $a(\lambda x)$ is the measured attenuation value at λx, and attenuation values $A(\lambda 1)$–$A(\lambda j)$ can be estimated by multiplying the column vector $[a(\lambda x)$–$a(\lambda z)]$ with the estimation matrix. The number of rows or columns of the estimation matrix corresponds to the number of estimated attenuation values or measured attenuation values, respectively. The figure also shows an example when *j* attenuation coefficients are estimated from the three measured attenuation values. It should be noted that the estimation matrix differs from the fiber product. Typically, 3–5 measured values are required to estimate the O–L-band attenuation spectrum. For recently established Recommendation G.654.E, it is beneficial to know the attenuation spectrum for this type of fiber to design high-capacity terrestrial networks. The applicability of the estimation method described in Recommendation G.650.1 for G.654.E fiber was recently investigated, and the validity of the attenuation-spectrum estimation over the C–L band from two measured attenuation



(a) Example of calculation equation for estimating j^{th} value from three measure values



(b) Schematic diagram for loss estimation

Fig. 3. Schematic image of attenuation-estimation method described in G.650.1.

values was confirmed, and Recommendation G.650.1 was revised accordingly.

In summary, the recent revisions of fiber Recommendations have focused on how optical characteristics can be specified for supporting terrestrial core or submarine long-haul networks with increased capacity or bitrate signals.

3. Recent activities on SDM standardization

Network capacity has been increasing at a rate of a few tens of percent, and the capacity crunch with SMF networks will become a serious issue in the 2020s. To overcome the capacity limit of SMF, fibers for space division multiplexing (SDM) transmission have been intensely investigated. **Figure 4(a)** shows the conceptual images of SDM fibers. SDM fibers can be basically categorized into two: multi-core fiber or multi-mode fiber. Multi-core fiber has multiple cores within a cladding, and multi-mode fiber has multiple propagation modes within a core. In SDM transmission, multiple signals can be simultaneously transmitted through multiple cores or modes, achieving much higher capacity compared with that in SMF. Before SDM fibers can be used in telecom networks worldwide, it is necessary to establish an SDM fiber Recommendation in the same manner as the SMF Recommendations. It was proposed and agreed at ITU-T 2020's January meeting to start discussion on a new technical report for SDM optical fiber and cable. Although the content of this technical report is under discussion, it was agreed to include the related topics on cable, splice/connectors, and installing technologies. The main discussion pointes are: target application and benefits of SDM technology and categorization of SDM fiber. Regarding the target application for SDM technologies, it is important to compare technologies that use SMF to improve spatial density, such as high-fiber-count cable or reduced coating-diameter fiber technologies, as shown in **Fig. 4(b)**. Although various SDM fibers have been proposed, current multi-core fiber- or few-mode fiber-based SDM fiber is being discussed as a potential candidate of SDM fiber. It is expected that the fiber parameters and test methods for such fibers will be discussed and incorporated into this technical report. The tentative publishing year for this technical report is 2022. The discussion on SDM fiber standardization has been initiated in advance in Japan, and the current technical level or challenges for SDM standardization has/have been summarized as technical report-1077 entitled "Technical Report on Space

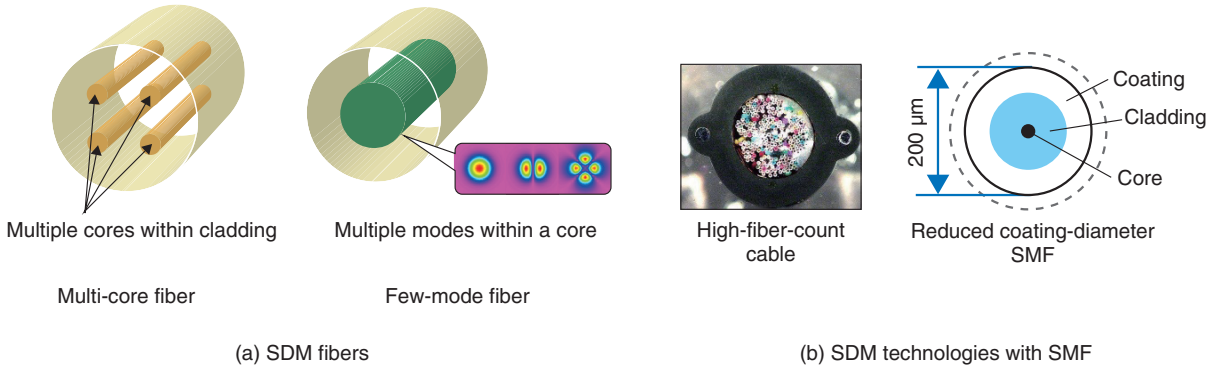


Fig. 4. SDM technologies discussed in ITU-T for developing new SDM technical report.

Division Multiplexing Technologies" (in Japanese) published by the Telecommunication Technology Committee (TTC) [2].

4. Summary

In ITU-T, the revision of SMF Recommendations has focused on how to support the increased capacity and bitrate transmission system over 100 Gbit/s, and each Recommendation has specified more detailed optical characteristics of the fiber. Regarding the SDM fiber standardization, the technical report on SDM fiber and cable, which will be published in 2022, is considered an important step in establishing an SDM fiber Recommendation. IEC has also decided to discuss the SDM fiber connector and amplifier standardization. We believe that SDM standardization, including fiber, cable or any other related component technologies, will be actively discussed and proceeded in cooperation with ITU-T and IEC.

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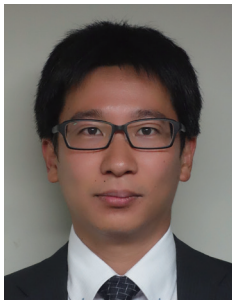

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Simulating Complex Quantum Networks with Time Crystals

1. Introduction

Researchers at the National Institute of Informatics (NII), NTT, Osaka University, the Japanese-French Laboratory of Informatics (JFLI), and Tokyo University of Science have discovered that time crystals can be used to simulate complex quantum networks.

Crystals are widely present in our daily life in the form of solid materials, the atoms of which self-organize in regular patterns. While these arrangements tend to be periodic in space, a newly discovered type of matter also shows such regularity in the dimension of time. These exotic systems are called *time crystals* and can only be observed under special circumstances. Although recent developments in quantum technology and the excellent controllability of quantum devices now allow researchers to explore time crystals in the laboratory, little is known about their properties and applications. This article, first published in Science Advances [1], focuses on the application of tools commonly used in network theory to represent these systems that allows for a deeper understanding of their structures. With this, researchers were able to represent the melting of a time crystal in terms of networks and found the emergence of special type of structures: scale-free networks. These complex networks have the same structural properties as today's Internet or airplane networks. Therefore, having a physical system that allows for its efficient simulation in the lab has enormous implications in the technology arena.

2. Background

Typical crystals emerge in nature as the atoms that form a solid arrange themselves in a periodic regular structure. When this occurs, a continuous translation symmetry of free space is broken, as the system is no longer invariant under the arbitrary translations of its atoms. The breaking of such a translation symmetry can also be done in the temporal dimension, giving raise to time crystals. A recent example of this phenomenon is presented as a twice the time discrete time crystal (2T-DTC). An arrangement of interacting two-level systems (such as spins) are under a periodic external drive that repeats at every time T. Time-translation symmetry breaking occurs when the dynamical response of the 2T-DTC shows a different periodicity than the external drive, as it needs 2T to go back to its initial position.

3. Research results

This research shows that complex network structures, such as scale-free networks illustrated in **Fig. 1**, emerge from slowly melting a 2T-DTC. The authors of this article used a model of a DTC that can be experimentally constructed and showed that its structure can be melted by adding an error to the drive (which plays the role of increasing temperature). Marta Estarellas from NII stated that, "Aided by a network visualization technique, for the first time we shed new light on the mechanisms by which the time crystal melts." Victor Bastidas from NTT added that, "It became clear that, with an increasing value of error, the melting of the time crystal behaves like a phase transition, something similar to the way crystals, such as a block of ice, typically melt."

4. Methods

Using Floquet theory, one can capture the periodic nature of time crystals and obtain information of the system at the relevant discrete points of its quantum dynamics. William Munro from NTT stated that, "We represented this information in terms of networks using a percolation rule and analyzed how its connectivity changes as the time crystal melts due to an error in the drive." The use of their network visualization technique made it possible to observe the temporal connection of the time crystal's quantum states for the first time, allowing them to extract information on

Fig. 1. Scale-free network emerging from the melting of a 2T-DTC.

the properties of the crystal by analyzing the properties of the crystal's associated network.

5. Outlook

Quantum computers exhibit enormous power even if they are small. Time crystals also present this advantage as they can embed exponentially large networks using a small time-crystal device. Marta Estarellas stated that, "Potential applications of our results include the use of time crystals as a quantum simulator to analyze the structure of very large complex networks present in our daily lives, something that in the classical world would otherwise be impossible as it would require a huge amount of computing resources." Kae Nemoto from NII added that, "Put it this way, using this method and with just several qubits one could simulate a complex network of the size of the entire worldwide Internet." Their introduced techniques proved networks to be a valuable tool to represent quantum complex systems, something that will surely aid in the future study and understanding of quantum many-body systems.

6. Funding

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* The opinions in this publication are those of the authors and do not necessarily reflect the views of the John Templeton Foundation.

Researcher's comment

Finding Real Applications for Current Quantum Devices

Marta P. Estarellas
Global Research Center for Quantum Information Science,
National Institute of Informatics

Quantum mechanics has had a huge impact on many areas of science by providing a whole new mathematical framework that helped – and keeps helping – us to enhance our knowledge of nature in a very accurate way. This theory is so powerful that its applications have soon reached the information science arena, giving rise to what could be – if not yet – a new technological revolution. The fast development of quantum technology has brought the field of quantum computing into the era of noisy intermediate-scale quantum (NISQ) devices. Proving quantum supremacy in such quantum devices has become a race between large academic institutions and companies. Their main focus is to attain the quantum advantage from the universal computation point of view. It is however unlikely that, with their current size and error rates, NISQ devices will be able to outperform conventional computers.

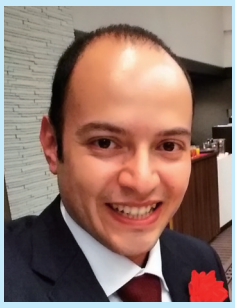
Under the QLEAP umbrella, NII and NTT Basic Research Laboratories are pursuing the quantum advantage proof from a different perspective: thinking of NISQ devices as dedicated systems. In our collaboration, we focus on the design of small-scale quantum devices with hardware-specific applications that surpass the current classical technology, without the need of granting for universality. With this aim, we have successfully proposed DTCs as dedicated quantum computers to simulate and analyze the structure of very large complex networks present in our daily lives, something that in the classical world would otherwise be impossible as it would require a huge amount of computing resources.

Researcher's comment

Melting Time Crystals to Simulate Networks on Small Quantum Computers

Victor M. Bastidas
Theoretical Quantum Physics Research Group,
Quantum Science and Technology Laboratory,
NTT Basic Research Laboratories

Crystals, such as salt and diamonds, are periodic arrays of atoms in space that are pretty common in our daily life. It has recently been demonstrated that time can be crystalized as well and the corresponding state of matter is known as a discrete time crystal (DTC). In contrast to spatial crystals, DTCs break discrete translational symmetry and time. They are rigid and robust against small perturbation and remain stable for a long time, as solid crystals do. Although DTCs are extremely popular in research and for the general public, practical applications of this exotic state of matter are lacking. In October 2020, we proposed a scheme to use DTCs to simulate a large-scale network. Our work is published in the American Journal Science Advances and will open a new avenue of research in the field of time crystals. We showed the possibility to simulate large networks with an exponential number of nodes by using small quantum devices.



This achievement was obtained through joint research with M. P. Estarellas and Prof. K. Nemoto from NII, T. Osada and Prof. K. Sanaka from Tokyo University of Science, B. Renoust from Osaka University, and W. J. Munro from NTT Basic Research Laboratories under the QLEAP program. Our work not only proposes an application of DTCs but opens a new direction of research. We envision that the methods and techniques developed from our work will inspire further research on global properties of systems out of equilibrium and their intimate relation with networks.

For inquiries:
Public Relations, NTT Science and Core Technology Laboratory Group
https://www.ntt.co.jp/news2020/2010e/201016a.html

World's Fastest Directly Modulated Laser Exceeding 100-GHz Bandwidth

1. Introduction

NTT in collaboration with Fumio Koyama, professor at the Laboratory for Future Interdisciplinary Research of Science and Technology, Tokyo Institute of Technology, has developed a membrane laser that uses an indium phosphide (InP) compound semiconductor on a silicon carbide (SiC) substrate with high thermal conductivity. This laser, the world's first directly modulated laser with a 3-dB bandwidth exceeding 100 GHz, can transmit at 256 Gbits (256 billion bits) per second over a distance of 2 km.

Directly modulated lasers are now widely used in datacenter interconnections, but their modulation speed is limited, which has been a problem for further increasing transmission capacity. Our membrane laser will enable us to respond to the expected increase in traffic with a low-cost and low-power-consumption solution and contribute to the development of a high-capacity optical transmission infrastructure that supports NTT's IOWN (Innovative Optical and Wireless Network). This research was reported in Nature Photonics on October 19, 2020 [1].

2. Research results

To increase the relaxation oscillation frequency, NTT researchers have focused on the optical confinement factor of the active region and developed a membrane laser on a silicon (Si) substrate with a thermal oxide (e.g., silicon dioxide (SiO_2)) film. Membrane lasers have a large optical confinement factor in the active region and are compact, making it possible to develop directly modulated lasers with low power consumption. Since such devices are fabricated on a low-thermal-conductivity SiO_2 layer, the temperature increase in the active layer due to current injection is large. Even if the current is increased, the relaxation oscillation frequency saturates at about 20 GHz due to saturation of the differential gain.

To suppress the increase in the active-region temperature, we fabricated InP-based membrane lasers on a SiC substrate, which has a thermal conductivity approximately 500 times higher than that of SiO_2. Since SiC has a lower refractive index than InP, the optical confinement factor is almost the same as that of the device on SiO_2. The membrane laser was fabricated by direct bonding with ultrathin (40 nm) SiO_2 between the InP layer and SiC substrate. Assuming a 100-mW heat source, the temperature increase in the active region of a membrane laser with an active layer length of 50 μm was significantly reduced from 130.9 to 16.8°C when the SiO_2 thickness was reduced from 2 μm to 40 nm. The current at which the relaxation oscillation frequency reaches its maximum was 5.5 mA for a membrane laser fabricated on SiO_2/Si substrate. In contrast, with the membrane laser fabricated on SiC substrate, we were able to increase the current to 30 mA and obtain the world's highest relaxation frequency of 42 GHz and a 3-dB bandwidth of 60 GHz.

In addition, using optical feedback from the end facet of the output waveguide, we designed the device in which photon-photon resonance occurs at around 95 GHz. As a result, we obtained a 3-dB bandwidth of 108 GHz and succeeded in generating a 256-Gbit/s (256 billion bits per second) pulse amplitude modulation (PAM)-4 signal and transmitting it over a distance of 2 km (**Fig. 1**).

3. Future developments

The future will see the development of transmitters capable of handling the next generation of Ethernet standards with transmission capacity exceeding 1 terabit with four or eight arrays. The simultaneous achievement of low power consumption is expected to suppress increases in the power consumption of datacenters and supercomputers due to the anticipated increase in data volume.

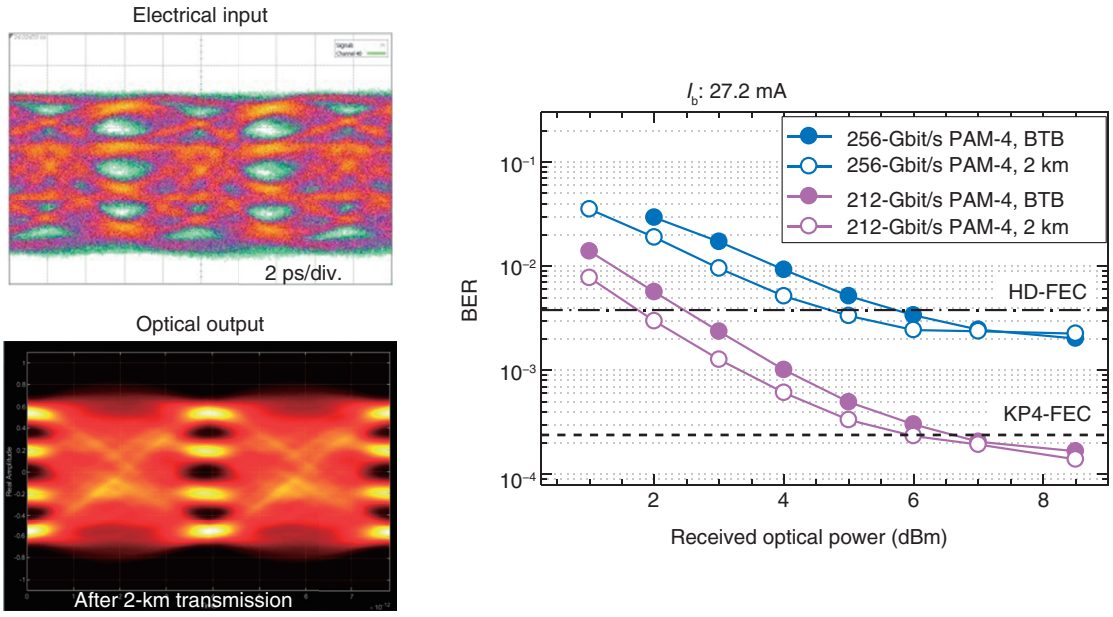


Fig. 1. Generation of 256-Gbit/s PAM-4 signal and bit error rate (BER) measurement results for back-to-back (BTB) and 2-km transmission. At the BERs below the dash-dotted line, data can be transferred without error using forward error correction (FEC).

Reference

[1] S. Yamaoka, N.-P. Diamantopoulos, H. Nishi, R. Nakao, T. Fujii, K. Takeda, T. Hiraki, T. Tsurugaya, S. Kanazawa, H. Tanobe, T. Kakitsuka, T. Tsuchizawa, F. Koyama, and S. Matsuo, "Directly Modulated Membrane Lasers with 108 GHz Bandwidth on a High-thermal-conductivity Silicon Carbide Substrate," Nat. Photon., Vol. 15, pp. 28–35, Oct. 2020.

For inquiries:
Public Relations, NTT Science and Core Technology Laboratory Group
https://www.ntt.co.jp/news2020/2010e/201020a.html

Demonstration of a Novel Method to Generate Chaotic Signals Using a MEMS Oscillator

1. Introduction

NTT and Tokyo Institute of Technology have demonstrated for the first time a simple and generic method of generating chaotic signals using a microelectromechanical oscillator. Using chaotic signals in information technologies, such as machine learning and secure communications, has been extensively studied. It is important to develop an efficient method of generating chaotic signals using on-chip devices. A microelectromechanical systems (MEMS) oscillator is a promising device for this purpose and has advantages of high integration capability and precise electrical control. With our method, we succeeded in generating chaotic signals using the libration of a MEMS oscillator with one-order of magnitude lower voltage than previous methods. Our method also enables the integration of a chaos generator with standard MEMS devices, such as ultrasmall microphones and sensors. The method enables machine learning of the output data from these devices directly on a common semiconductor chip.

The above results were obtained though the collaboration of NTT, where the device fabrication and measurement were conducted, with Tokyo Institute of Technology, where the data analysis was conducted on the basis of the theoretical calculations. The results were published in Physical Review Letters on October 23, 2020 [1].

2. Background

Chaos is a commonly observed phenomenon in various physical environments. Its temporal change looks apparently random, but also exhibits regular and deterministic behavior governed by simple laws of nature. There have been various studies on using the complex behavior of chaos in information technologies, such as machine learning, secure communications, and random-number generation.

MEMS is a type of fine structure device that functionalizes the physical motion of the composing elements. MEMS is used in many practical systems such as high-performance sensors, high-frequency filters, and digital mirror devices. Producing chaotic signals using a MEMS oscillator was proposed some years ago as a promising technology for processing the output data from MEMS sensors, but this technology has not progressed due to the problem that chaos generation using standard MEMS technologies requires a large area of electrodes as well as high applied voltage up to several tens of volts. We propose a method for solving this problem by using libration of a MEMS oscillator. This method generates chaotic signals simply by applying two different frequencies of electric signals. The efficiency is so high that we do not need high voltage or large electrode structures; therefore, highly integrated devices with low operation voltage can be fabricated.

3. Device structure and achievements

The MEMS device used in the demonstration consists of a suspended mechanical oscillator called a doubly clamped beam. The device was fabricated by processing a piezoelectric semiconductor, with which an alternate voltage is applied to induce mechanical vibration. We confirmed that the voltage including two frequencies generates libration, and aperiodic oscillation starts when the motion becomes large (**Fig. 1**). Theoretical analysis confirmed that the observed signal has the features expected for chaos. The voltage required to generate chaos was only a few volts, which is one order of magnitude smaller than with previous methods. We succeeded in generating chaotic signals with such small voltage using a simple beam structure.

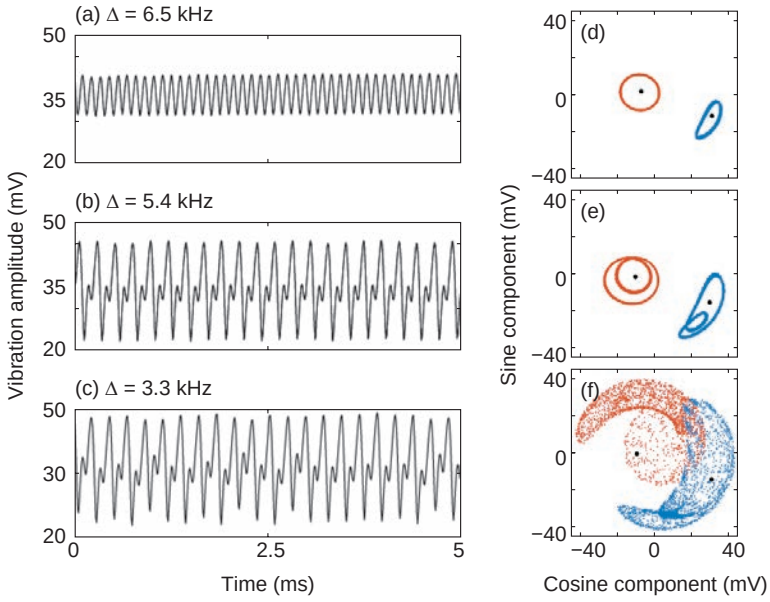


Fig. 1. Dependence of measured mechanical vibration on the applied frequency difference (Δ).

4. Outlook

The frequency of mechanical vibration in this study is several megahertz, which is not high enough for practical applications. Therefore, we aim to generate chaotic signals at higher frequencies. After succeeding in fabricating such high-frequency devices, we will focus on practical applications of these devices such as for reservoir computation and secure communication.

Reference

[1] S. Houri, M. Asano, H. Yamaguchi, N. Yoshimura, Y. Koike, and L. Minati, "Generic Rotating-frame-based Approach to Chaos Generation in Nonlinear Micro- and Nanoelectromechanical System Resonators," Phys. Rev. Lett., Vol. 125, 174301, Oct. 2020.

Researcher's comment

Toward Emergent Computing

Ludovico Minati
Specially Appointed Associate Professor,
Institute of Innovative Research, Tokyo Institute of Technology

Nature does not work like a digital computer. The incredible complexity of the biological, social, and physical world is created by phenomena that follow simple rules. These rules are universal and nonlinear. They can produce many phenomena, including chaotic movements. Chaotic movements are irregular and can be synchronized in complex ways. Therefore, it is possible to generate complex patterns such as those found in the brain. These patterns can one day help generate and analyze information.

Chaotic motion is usually generated using electronic circuits. Many types and components are possible and I have studied them. However, the characteristics of electronic components are not ideal, e.g., using a battery for a long time wastes energy and vibration resonance is not so sharp. Optical and mechanical devices fabricated on a nanoscale are far superior to transistors.

In collaboration with NTT Basic Research Laboratories, we were able to develop a device that can generate chaotic mechanical vibrations very easily. Due to its very simple structure, many operations are possible. We will continue to collaborate to create a network of such devices.

Researcher's comment

Towards Nanosystem-based Mechanical Brains

Samer Houri
Research Specialist,
NTT Basic Research Laboratories

The fields of oscillator networks and network dynamics are currently witnessing astonishing progress both in terms of the theoretical understanding of such complex systems as well as their implementation in a variety of information processing applications such as artificial intelligence. The high computational load of conventional neural networks has prompted alternative designs of network-based information processing systems; among them is reservoir computation.

In applications in which fast throughput and low power constraints are dominant, e.g., edge computing, the computationally heavy task of training a neural-network-based system is not acceptable; therefore, neural networks are replaced with nonlinear networks, i.e., a reservoir, the connections of which remain unmodified and the task of training is greatly simplified.

Our research aims to create efficient reservoir-computation platforms using micro- and nano-electromechanical systems (M/NEMS) as the infrastructure. MEMS and NEMS-based devices provide an excellent tool for the implementation of the highly nonlinear functions required for efficient reservoir computation.

We recently demonstrated a path towards low-power generation of chaos and identified the region where the edge of chaos exists. The edge-of-chaos region is highly suitable at separating its inputs in a high-dimensional and abstract phase-space. Since such inputs represent information to be processed, the system is therefore capable of separating inputs into categories, such as distinguishing images or identifying patterns.

We foresee exciting possibilities for the use of M/NEMS platforms for such applications, especially because they can be easily fabricated in large numbers to produce very high-dimensional reservoirs, and are able to react to external stimuli, thus combining both the functions of sensors and information processors.

For inquiries:
Public Relations, NTT Science and Core Technology Laboratory Group
http://www.brl.ntt.co.jp/E/2020/10/latest_topics_202010241444.html

External Awards

DCASE 2020 Challenge Judges' Award
Winners: Yuma Koizumi, NTT Media Intelligence Laboratories; Daiki Takeuchi, Yasunori Ohishi, Noboru Harada, Kunio Kashino, NTT Communication Science Laboratories
Date: November 1, 2020
Organization: DCASE (Detection and Classification of Acoustic Scenes and Events) Community

For "The NTT DCASE2020 Challenge Task 6 System: Automated Audio Captioning with Keywords and Sentence Length Estimation."
Published as: Y. Koizumi, D. Takeuchi, Y. Ohishi, N. Harada, and K. Kashino, "The NTT DCASE2020 Challenge Task 6 System: Automated Audio Captioning with Keywords and Sentence Length Estimation," DCASE2020 Challenge, Mar.–July 2020.

Certificate of Appreciation
Winner: Seishi Takamura, NTT Media Intelligence Laboratories
Date: December 31, 2020
Organization: The Institute of Electrical and Electronics Engineers (IEEE) Region 10

For his dedicated services and commitment as the 2019 & 2020 IEEE Region 10 Treasurer.

IEEE Fellow
Winner: Tomohiro Nakatani, NTT Communication Science Laboratories
Date: January 1, 2021
Organization: IEEE

For his contributions to far-field signal processing for speech enhancement and recognition.

Papers Published in Technical Journals and Conference Proceedings

Distributed Server Allocation Model with Preventive Start-time Optimization against Single Failure
S. Masuda, F. He, A. Kawabata, and E. Oki
Proc. of the IEEE 21st International Conference on High-Performance Switching and Routing (HPSR 2020), May 2020.

This paper proposes a distributed server allocation model with the preventive start-time optimization against a single server failure. The proposed model preventively determines the assignment of servers to users under each failure pattern to minimize the largest maximum delay among all failure patterns. We formulate the proposed model as an integer linear programming problem. We prove the NP (nondeterministic polynomial time)-completeness for the considered problem. The numerical results reveal that the proposed model reduces the largest maximum delay compared to one baseline; it avoids instability caused by the unnecessary disconnection, which frequently occurs in the other baseline.

Participating-domain Segmentation Based Server Selection Scheme for Real-time Interactive Communication
A. Kawabata, B. C. Chatterjee, and E. Oki
IEICE Transactions on Communications, Vol. E103-B, No. 7, pp. 736–747, July 2020.

This paper proposes an efficient server selection scheme in successive participation scenario with participating-domain segmentation. The scheme is utilized by distributed processing systems for real-time interactive communication to suppress the communication latency of a wide-area network. In the proposed scheme, users participate for server selection one after another. The proposed scheme determines a recommended server, and a new user selects the recommended server first. Before each user participates, the recommended servers are determined assuming that users exist in the considered regions. A recommended server is determined for each divided region to minimize the latency. The new user selects the recommended available server, where the user is located. We formulate an integer linear programming problem to determine the recommended servers. Numerical results indicate that, at the cost additional computation, the proposed scheme offers smaller latency than the conventional scheme. We investigate different policies to divide the users' participation for the recommended server finding process in the proposed scheme.

Algorithms for Distributed Server Allocation Problem
T. Sawa, F. He, A. Kawabata, and E. Oki
IEICE Transactions on Communications, Vol. E103-B, No. 11, pp. 1341–1352, November 2020.

This paper proposes two algorithms, namely server-user matching

(SUM) algorithm and extended server-user matching (ESUM) algorithm, for the distributed server allocation problem. The server allocation problem is to determine the matching between servers and users to minimize the maximum delay, which is the maximum time to complete user synchronization. We analyze the computational time complexity. We prove that the SUM algorithm obtains the optimal solutions in polynomial time for the special case that all server-server delay values are the same and constant. We provide the upper and lower bounds when the SUM algorithm is applied to the general server allocation problem. We show that the ESUM algorithm is a fixed-parameter tractable algorithm that can attain the optimal solution for the server allocation problem parameterized by the number of servers. Numerical results show that the computation time of ESUM follows the analyzed complexity while the ESUM algorithm outperforms the approach of integer linear programming solved by our examined solver.

Power of Uninitialized Qubits in Shallow Quantum Circuits

Y. Takahashi and S.Tani

Theoretical Computer Science, Vol. 851, pp. 129–153, January 2021.

We study uninitialized qubits, whose initial state is arbitrary and unknown, in relation to the computational power of shallow quantum circuits. To do this, we consider uniform families of shallow quantum circuits with n input qubits, $O(\log n)$ initialized ancillary qubits, and $n^{O(1)}$ uninitialized ancillary qubits, where the input qubits only act as control qubits. We show that such a circuit with depth $O((\log n)^2)$ can compute any symmetric Boolean function on n bits that is computable by a uniform family of polynomial-size classical circuits. Since it is unlikely that this can be done with only $O(\log n)$ initialized ancillary qubits, our result provides evidence that the presence of uninitialized ancillary qubits increases the computational power of shallow quantum circuits with only $O(\log n)$ initialized ancillary qubits. On the other hand, to understand the limitations of uninitialized qubits, we focus on sub-logarithmic-depth quantum circuits and show the impossibility of computing the parity function on n bits.

Graph-based Regional NMF for Distributed Computing

T. Koshizuka, K. Takeuchi, T. Matsubayashi, and H. Sawada

IPSJ Journal, Vol. 62, No. 1, pp. 387–396, January 2021.

Non-negative matrix factorization (NMF) is a popular unsupervised pattern recognition technique for the analysis of aggregated data. In particular, non-negative multiple matrix factorization (NMMF) treats common elements from multiple data as common factors, and execute simultaneous decomposition effectively. In this study, we propose a novel matrix factorization method called regional non-negative matrix factorization (rNMF), which factorises multiple matrics simultaneously, focusing on physical relation between aggregated data such as regional characteristics in addition to common factors. rNMF expresses data of physically close areas in a similar feature space, and extracts intuitively interpretable bases and coefficients from multiple matrics. The information of regional location is given by a graph. Furthermore, by solving the graph coloring problem heuristically, rNMF works at high speed on a distributed system even if the analyzed data are large matrices. In this paper, we formulate rNMF as an extended version of NMF and derive multiplicative update rules for parameter estimation. We performed experiment with real data, which were aggregated by region, in order to verify that rNMF can expresses adjacent regional data in a common feature, rNMF attained similar generalization performance as the original NMF, and rNMF works at high speed on a distributed system.

Optimal Server Selection Scheme with Optimistic Synchronization for Delay Sensitive Service

A. Kawabata, B. C. Chatterjee, and E. Oki

Proc. of the 18th IEEE Consumer Communications & Networking Conference (CCNC 2021), Virtual conference, January 2021.

In distributed processing for communication services, a proper server selection scheme is required to suppress delay by ensuring the event occurrence order. Although a conservative synchronization algorithm (CSA) has been used in this issue, an optimistic synchronization algorithm (OSA) can be a potential candidate for synchronizing distributed systems. In comparison with CSA, which reproduces events in occurrence order before processing application, OSA can be feasible to realize low delay communication as the processing events arrive sequentially. This paper proposes an optimal server selection scheme considering OSA for distributed processing systems to minimize end-to-end delay under the condition that the holding time for application status is limited. In other words, the endtoend delay is minimized based on the allowed rollback time for application design or quality-of-service. Numerical results indicate that the delay of the proposed scheme can be reduced by up to a quarter compared to that of the conventional scheme that is based on CSA.
