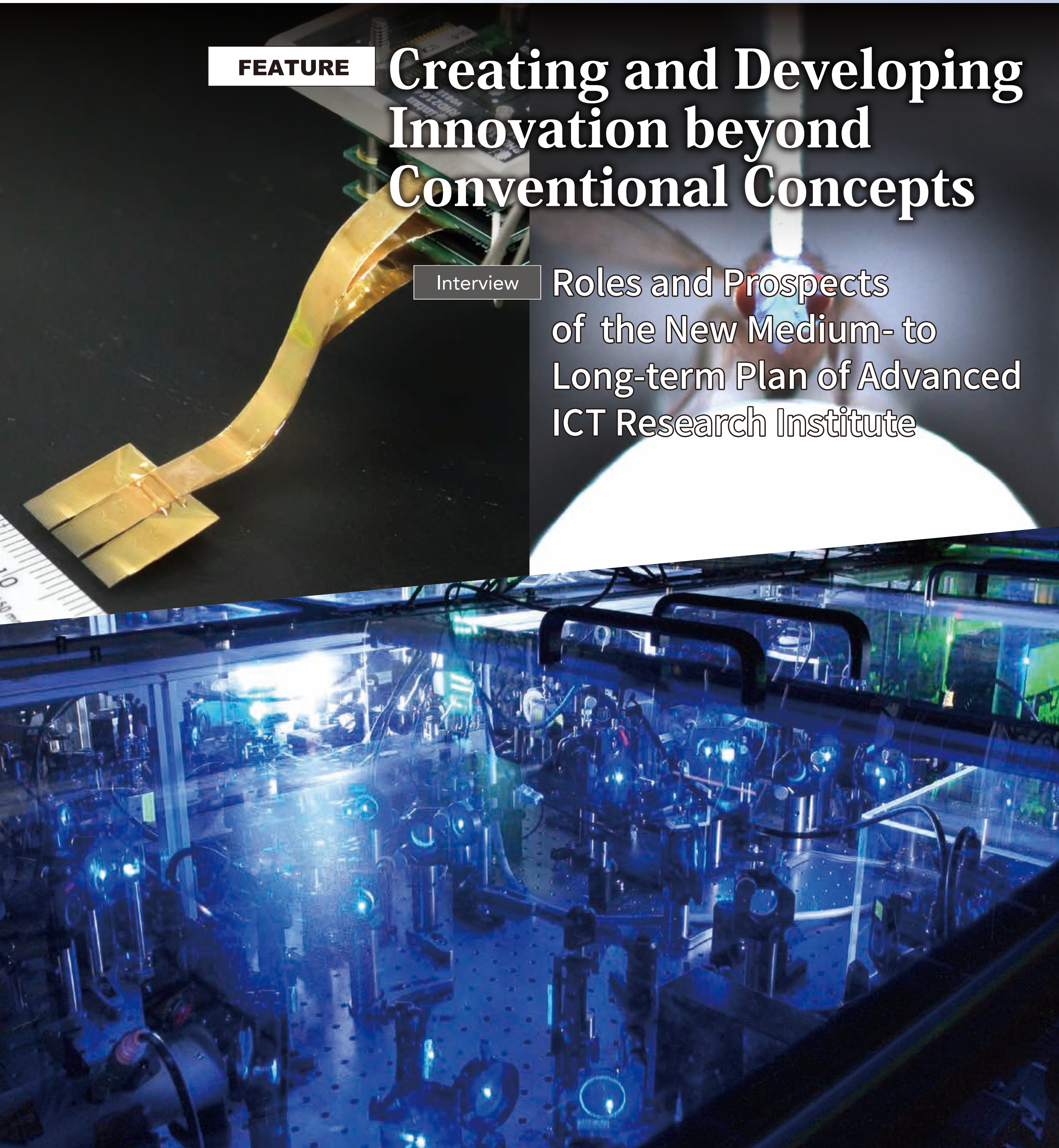
NICT NEWS

National Institute of
Information and Communications
Technology

No.5
2021
Vol.489



FEATURE

Creating and Developing Innovation beyond Conventional Concepts

Interview

Roles and Prospects of the New Medium- to Long-term Plan of Advanced ICT Research Institute

NICT NEWS 2021 No.5 Vol.489

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CONTENTS

FEATURE

Creating and Developing Innovation beyond Conventional Concepts

Interview

TOPICS

Cover Photo：
The Advanced ICT Research Institute in charge of frontier science research is committed to pursuing "the creation and development of innovations beyond conventional ideas."
From the New Medium- to Long-term Plan, the Institute takes charge of the Center for Information and Neural Networks (CiNet), and aims to integrate different fields and initiate entirely new research.

Photo Upper Left：Deep ultraviolet semiconductor light source
Deep ultraviolet semiconductor light sources are expected to be used as an alternative to existing mercury lamps.

Roles and Prospects of The New Medium- to Long-term Plan of Advanced ICT Research Institute





WADA Naoya

Director General, Advanced ICT Research Institute

Joined the Communication Research Laboratory (currently NICT) in 1998. After serving as Director of the Photonic Network Laboratory and Director General of the Network System Research Institute, he assumed office as Director General of the Advanced ICT Research Institute in 2020.
Ph.D. (Engineering)

KUBOTA Toru

Director General, Kobe Frontier Research Center, Advanced ICT Research Institute

In 1997, joined the Communication Research Laboratory (currently NICT) and the Kansai Advanced Research Center (currently Advanced ICT Research Institute). He has been engaged in research on organic molecular electronics. After serving as Director of the Promotion Office and then Associate Director General of the Advanced ICT Research Institute, he assumed his current post in 2021.
Ph.D. (Engineering)

KASAMATSU Akifumi

Director General, Koganei Frontier Research Center, Advanced ICT Research Institute

Joined the Communication Research Laboratory (currently NICT) in 2002. After serving as Director of the Terahertz ICT Device Laboratory and Executive Researcher of the Frontier Research Laboratory, he assumed his current post in 2021. He has been engaged in research and development on millimeter- and terahertz-wave wireless communication technology.
Ph.D. (Engineering)

YANAGIDA Toshio

Director General, Center for Information and Neural Networks, Advanced ICT Research Institute

After dropping out of the Ph.D. program at graduate school, then later serving as professor of Osaka University and Distinguished Researcher of NICT, he assumed his current post in 2013. He has studied the mechanisms of life based on fluctuations. Awarded Person of Cultural Merits in 2013.
Ph.D. (Engineering)

Under the 5th Medium- to Long-term Plan of NICT, which started in April 2021, the organizational structure has been transformed to adapt to the changing times. NICT is conducting research and development by using its five research laboratories as key organizations in the five priority areas indicated by the five keywords: Observing, Connecting, Creating, Protecting, and Developing. Among these, the Advanced ICT Research Institute, which is expected to develop new horizons in ICT, took charge of the Center for Information and Neural Networks (CiNet) and thus now covers a broader scope under the new Plan.

We asked Director General WADA Naoya, and each Director General of the three centers, YANAGIDA Toshio of CiNet, KUBOTA Toru of the Kobe Frontier Research Center, and KASAMATSU Akifumi of the Koganei Frontier Research Center, about the roles, prospects, and aspirations of the Institute which has made a new start.

Pursuing the basics, including more academic areas

— First, I would like to ask General Director Dr. WADA to give an overview of his organization, which has embarked on a new era under the New 5th Medium- to Long-term Plan.

WADA: The Advanced ICT Research Institute is a research laboratory that studies the most basic areas among the five laboratories in NICT. Although this role remains the same, the new Plan has made two major changes.

The first is that under the previous Plan, our Institute was responsible for frontier research, but now the term “science” has been clearly added. We originally focused on basic research, but adding “science” to the name clarifies the new stance of promoting research including more academic areas.

The second change is that CiNet, which was a separate organization, has been merged into the Advanced ICT Research Institute. The existing research fields we have dealt with cover a comparatively wide range such as quantum computing, high frequencies, new devices, and even biotechnology. By absorbing CiNet, which has handled brain research, our scope has expanded and our organization is now

Interview

Roles and Prospects of The New Medium- to Long-term Plan of Advanced ICT Research Institute

the biggest among the five laboratories in NICT. These two changes are particularly significant.

As I mentioned in the Frontier Science Symposium 2021 held on May 28 by the Advanced ICT Research Institute, one of the main objectives for the entire institute is “the creation and development of innovations beyond conventional ideas.”

Our research spans from basic research in various fields to advanced areas including engineering. We will integrate different fields by leveraging our breadth of study within the Institute, and as a result, will initiate entirely new areas of research.

The research system for the existing frontier research field has been divided into two research centers: Koganei and Kobe. And, as CiNet is already a single organization in the Suita campus of Osaka University, it has joined the Advanced ICT Research Institute as it is. We will carry out our research at these three sites.

Roles of the three research centers

— Regarding the organizational change, Mr. WADA just mentioned that the key change is that CiNet at Suita is now under the umbrella of the Institute. Director General YANAGIDA, could you explain what will change as a result of joining the Institute?

YANAGIDA: Brain research is a fascinating field with a vast number of researchers engaged in it around the world, and yet much remains unknown and the research may not yield great success in the short term. Thus, it is a typical field that is still at the stage of where we must concentrate on the science, or basic study, in parallel with engineering. Without doubt, brain research has great potential to influence ICT and many other fields in the future.

CiNet was funded with the aim of using brain science in the information field. Brain research might sound like a field of biology such as cytobiology or neurophysiology, but CiNet is characterized by many researchers who come from backgrounds in information science and physics. Currently, artificial intelligence (AI) is booming, and I believe CiNet is a unique entity that could serve as a bridge between natural intelligence and artificial intelligence.

— What might be the effects of CiNet with its unique characteristics joining the Advanced ICT Research Institute?

I talked with Director General WADA about this the other day. The human brain can find reasonable solutions with little energy from a huge number of complicated elements with almost infinite combinations. I myself am most fascinated by this aspect of brain function. It is truly mysterious compared to AI, which consumes a lot of energy (calculation) to get answers from many combinations of elements. I feel that brain function is closely linked with quantum annealing. Considering this relationship, our field of brain research is highly likely to get hints from researchers engaged in quantum computing. Conversely, a biological algorithm we are studying could be applied to quantum computers. I believe that solving even a part of the extraordinary energy-saving algorithm of the brain in an elementary manner could greatly contribute to the challenges of modern ICT.

— Next, I would like to ask Director General KUBOTA of the Kobe Frontier Research Center. We have just heard that the two frontier research centers are not divided precisely by fields but have overlapping parts; what are the characteristics of the Kobe Center?

KUBOTA: Originally, the Advanced ICT Research Institute started out in Kobe. I take pride in the fact that we have been steadily working with researchers on foundations in various other fields throughout the history of the Institute. I believe that the Kobe Center is characterized by the fact that it works in many fields.

Specifically, we have the Bio-ICT Laboratory, which works at the microbiology level such as cells and proteins, and the Superconductive ICT Device Laboratory, which conducts basic research on superconductivity for physics, and the Nano-scale Functional Assembly ICT Laboratory, which is studying light using organic materials. There is also the DUV ICT Device Laboratory, which is working with researchers on deep UV LEDs; this field is very close to practical application. In addition to these existing laboratories, the Neuro-ICT Laboratory started this fiscal year in the new field related to biology. This laboratory will conduct research on intermediate areas connecting the functions of microbiology described before with macro networks such as brain information.

The environment allows researchers to

study a wide range of basic and fundamental areas under its own spirit, because it is far from the headquarters in Koganei. Of course, this has both positive and negative sides, but I hope to harness this unique characteristic in a good way, so that it doesn't have negative effects.

Kobe has accumulated much expertise through continuous academic research since it was founded, and its outputs are high quality. As we continue to conduct basic and fundamental research over the next 10 and 20 years, we will naturally produce applications, and we will continue to conduct research accordingly. Regarding applied research, the conventional way is first to conduct basic research steadily until finally reaching the level of applied research. However, we might be able to reach that stage without conducting many basic studies if we could successfully produce good results from basic and fundamental research. As examples, deep UV LED could be used to eradicate new types of coronaviruses, superconducting devices are expected to be used for quantum ICT networks, and optical devices made of organic materials could be used for terahertz applications in Beyond 5G. As these examples indicate, research on the next level of networks for the future is also progressing.

I also want to promote and develop new possibilities and fields that are suitable for young researchers to actively challenge.

I hope we can work on all of these as one of the features of our Kobe Frontier Research Center.

— Next, I would like to ask Director General KASAMATSU about the features and major activities of the Koganei Frontier Research Center.

KASAMATSU: As a matter of fact, the Advanced ICT Research Institute has not determined officially that Koganei and Kobe play different roles. The Koganei Frontier Research Center was founded by combining three laboratories, namely, Quantum ICT Laboratory, Green ICT Device Laboratory, and Terahertz ICT Device Laboratory, for geographical convenience because they were located in Koganei.

Light and electromagnetic waves have the characteristics of both waves and particles. The Quantum ICT Laboratory focuses on the latter and applying it to various forms of ICT. One example is to use the quantum mechanical property of light for encryption in networks. The Laboratory aims to achieve encryption that cannot be decoded regardless of how powerful computers become in the future. Another research area is applying the quantum property of light to nodes in networks. In addition, it is conducting research on the more-distant future, such making various computers more powerful by using the physical quantum properties.

As the word "Green" in its name indicates, the Green ICT Device Laboratory conducts research on devices that have less environmental load. Specifically, it is researching devices that use gallium oxide for elements with characteristics such as high voltage resistance, low transmission loss, and high radiation resistance. Although gallium oxide is a known substance, NICT has been researching and developing devices using the substance ahead of other countries, and is proud to be a leader in this field.

Finally, the Terahertz ICT Device Laboratory is using high-frequency radio waves such as millimeter and terahertz waves for ICT, and is researching the devices and systems required. Terahertz waves are at frequencies between the radio waves used in conventional cell phones and wireless LAN, and visible light or the light used in optical communication. Thus, we are studying technologies used for both conventional wireless devices and optical ones, and integrating them.

The ultrahigh frequency band has a wide range of unused frequencies and is expected to be used in Beyond 5G or 6G.

■ Prospects for the Advanced ICT Research Institute in the new era

— I would like to ask each of you for your opinions on the future prospects

Kobe Frontier Research Center
Superconductive ICT Device Laboratory, Nano-scale Functional Assembly ICT Laboratory ,Bio-ICT Laboratory, Neuro-ICT Laboratory, DUV ICT Device Laboratory, Quantum ICT Laboratory (Kobe) Terahertz ICT Device Laboratory (Kobe)

Koganei Frontier Research Center
Planning Office, Quantum ICT Laboratory, Terahertz ICT Device Laboratory, Green ICT Device Laboratory

Interview

Roles and Prospects of The New Medium- to Long-term Plan of Advanced ICT Research Institute

and any message you may have for other researchers.

WADA: As the New Medium- to Long-term Plan has just begun, I think it is important to work on definite prospects. First, as I mentioned at the beginning, we need to improve our research activities, including the science that lies behind each research. We have worked with basic parts so far, but I think we need to study our fields in much greater depth academically.

On the other hand, we must always remember the opposite direction. We conduct basic research, but there is much concern now about how the results can be used for the world. Answering this question is a huge challenge for our Institute. Of course, I cannot give a specific answer now, but I think we should continue to consider possible answers, including with the young researchers in every research center and every laboratory under each center.

We have focused on basic research the results of which may take 20 or 30 years to materialize. As Director General KUBOTA mentioned before, some of our results could be used partially on a trial basis in the world. Once we release them to the world, we will get feedback. Even though some of them will be evaluated as worthless, we should not give up but must consider why they are no good, and then use that knowledge for our basic research.

For this reason, I always tell everyone in my Institute that, while conducting their basic research, they should always be conscious of how the results can be applied in the world.

KASAMATSU: This point has something to do with the differences between Koganei and Kobe. Some subjects tackled by the Koganei Frontier Research Center are expected to be implemented in society in the near future, although some happen "accidentally."

There are three laboratories in Koganei, the oldest with a history of 20 years or more and the newest with about 10 years, so they conduct research for long time spans. They handle a mix of research: some studies take 20 or 30 years before full implementation, while others might be released by the end of the New Medium- to Long-term Plan. As Director General WADA said, the research time spans vary. So, while some research results must be released steadily to the world, other research in the same field is looking at 20 to 30 years from now.

Of course, this does not mean that Kobe is different from Koganei, but I believe that Koganei has a particularly strong tendency toward this, which is one of its characteristics.

KUBOTA: Definitely, Kobe generally handles foundation research, and the tendency is as Director General KASAMATSU has mentioned. However, I believe Kobe has a key characteristic and role of encouraging new shoots looking at decades ahead, offset against more immediate results.

To borrow from Director General YANAGIDA's favorite slogan of "delightful research" for CiNet, we are pursuing "delightful basic research" (everyone laughs). That's my policy.

YANAGIDA: Why did I come up with "Omoroi research"? As NICT is a government-run research organization, all research must contribute to society, that is, be mission oriented. However, if I just instruct my researchers to do things because it's our mission without listening to their opinions, it will not go well. To get good results ultimately, it is important for researchers themselves to determine their own research direction and be excited about their studies. By nature, researchers do not want simply to obey orders. Having said that, being a government-run organization we always have a mission. If such a mission starts penetrating the details of research, then conflict will arise between that mission and the researchers' ideas, and the researchers will lose motivation. Therefore, I will only show an overall direction and tell the researchers to proceed with their research freely within that. In other words, ideally, I always guide our researchers unobtrusively, and in the long run, everyone is heading toward a mission. I believe that Omoroi research is the best way to contribute to innovation of society and business, that is, all kinds of missions. Therefore, the sign "Omoroi research" is displayed at the entrance of the center to always remind researchers of their position.

"Omoroi" is Osaka dialect. It is expressed as "interesting" in Tokyo but is essentially different. Omoroi includes a sense of thrill and pleasure that is hard to describe with one word. It also implies that Omoroi research should thrill and impress many people, and thus lead them to innovation of society and business. "Omoroi research" may be harder to conduct than mission-oriented research in which one's tasks

Online interview held at NICT Headquarters (Koganei,Tokyo), Kobe, and Suita(Osaka)

Center for Information and Neural Networks (CiNet) at Suita, Osaka
Brain Networks and Communication Laboratory, Brain Function Analysis and Imaging Laboratory, Neural Information Engineering Laboratory

have already been determined. However, since researchers enjoy doing what they want, the hardships are not painful, and they can get over them. Of course, this may not be true for any research whose mission is completely determined. But as Director General WADA said, the policy stated by the Advanced ICT Research Institute includes “science.” This means we must also tackle research that has great potential for progress in the future even if we do not realize it now. In such cases, I think it is crucial to prepare an Omoroi environment where our researchers can work effectively with a sense of thrill and pleasure.

WADA: Compared to Director General YANAGIDA, I still need to establish a way of giving a sense of thrill to researchers (everybody laughs).

I have been asked about the differences as a researcher between being in NICT and being in a university. I find that universities tend to have more freedom in setting research subjects than NICT. On the other hand, since universities are educational organizations, we need to teach students. Students come to NICT as part of joint research, but NICT is basically a collection of researchers. Certainly, NICT has missions as a government-run research organization, but NICT researchers are allocated some budget when they are still comparatively young, and if they work hard, they can expand their permitted scope of research. In this sense, NICT has more freedom than universities.

YANAGIDA: Universities are not mission-oriented and so can study freely. However, laboratories are highly independent and rarely collaborate with each other, making it difficult for multiple laboratories to collaborate on large-scale research. NICT can do it. Also, it is very difficult for researchers to become a university professor while still young, and many hours are spent on assisting the professors. In this respect, in NICT, particularly in the Advanced ICT Research Institute, the researchers can be independent and focus on their own studies while still young, and enjoy more freedom of interdisciplinary research. As a result, several researchers in CiNet did good unique researches and were invited to become full professors at universities although they were still young.

I talked about “mission-oriented,” but I often think that people do not really know what their neighboring laboratories are doing in a university. Also, it is very difficult to become a university professor while still young, and many hours are spent on assisting the professors. In this respect, in NICT, particularly in the Advanced ICT Research Institute, the researchers can focus on their own studies while still young, and enjoy more freedom of interdisciplinary research.

WADA: That is true. As I said at the beginning of this symposium, I am particularly interested in generating new ideas by integrating entirely different fields in the next five years. In this respect, freedom for interdisciplinary exchange is critical. As Director General YANAGIDA said, we can find unexpected common aspects at the intersection of quantum science and brain function, and joint research has started in the fields of devices and biology at Kobe. It is important for us to consolidate further such environments.

— Thank you all for your time.

This interview was conducted online.

Unraveling the Circuit Mechanism Underlying Behavior in the "Microbrain" of an Insect

YAMAMOTO Daisuke

Director of Neuro-ICT Laboratory, Kobe Frontier Research Center, Advanced ICT Research Institute.

After serving as a researcher at Mitsubishi Kagaku Institute of Life Sciences, professor at Waseda University, and professor at the Graduate School of Tohoku University, he joined NICT in 2018. He assumed his current position in April 2021. He has been engaged in electrophysiological studies on neuronal excitation and synaptic transmission, and neurogenetic studies on behavior.
Doctor of Science.

KOHATSU Soh

Research Manager, Neuro-ICT Laboratory, Kobe Frontier Research Center, Advanced ICT Research Institute

After receiving his Ph.D., he served as a researcher at the Graduate School of Tohoku University. He joined NICT in 2018. He assumed his current position in April 2021. He has been engaged in neurogenetic studies on behavior.
Ph.D. (information science).

In April 2021, the Neuro-ICT Laboratory was launched in the Advanced ICT Research Institute to promote biomimetic approaches to the development of novel information technology. This laboratory consists of two groups: the memory neurobiology project and the behavior neurobiology project, both of which used to belong to the Frontier Research Laboratory. Both projects work with an insect (*Drosophila*) that quickly responds to stimuli in the outside world and produces highly flexible and diverse behaviors, despite its small brain; the volume of a fly brain is only 1/10000 of the human brain. The purpose of the projects is to apply the operating principles of such an efficient insect brain to social technology, including sensor information processing in IoT equipment. We aim to identify seeds for the development of new ICT that effectively operates even under unfavorable conditions, where, for example, computation resources and energy are extremely limited.

Learning from the insect brain, an extraordinarily efficient information processor

Insecta, to which *Drosophila* belongs, is the most successful animal taxon on earth. Without doubt, the secret of their success resides in functional specializations of the nervous system, which has evolved in unique ways under the strong selection pressure they experienced in adapting to harsh environments. In Vertebrata, at whose apex *Homo sapiens* stands, the brain has followed the path of centralization, increased size, and sophistication. On the other hand, insects with their small bodies have gained success by building niches in special environments, and have achieved adaptive behaviors by effectively combining their limited sensibilities and stereotypical behavioral repertories. In a sense, they demonstrate an adaptive strategy antithetical to that of humans. One of the results is the extremely compact brain: for example, *Drosophila* has only ~250,000 neurons housed in the brain with a volume of just 10^{-1} mm^3 (the human brain is 1.5×10^6 mm^3 in volume and has approximately 100 billion neurons; see Figure 1). *Drosophila* is widely used all around the world as a model for biological research and since Thomas Hunt Morgan in the US started using them for genetic studies, a vast collection of research resources has been accumulated. Sophisticated technology for controlling genes lies behind the advantage of *Drosophila* as a research subject; this technology makes it possible to visualize single neurons within the brain and manipulate the activities of neurons in living flies. Supported by such experimental techniques and the small number of neurons, a connectome project, which tries to completely identify the neural connections in the entire brain at the level of single neurons, is about to be completed for *Drosophila*. Against this backdrop, the brain study of *Drosophila* is entering a new area, aiming to identify all the neurons that form the neural circuits involved in specific information processing such as extracting characteristics from sensory inputs and decision-making, and thus understand the mechanism (algorithm) of the circuits. These unique properties of *Drosophila* as a research subject give unparalleled opportunities to explore, via a bottom-up, cell-to-circuit-to-behavior approach, algorithms for system control, with which simple neural circuits achieve precise and timely control of a series of complex actions. We believe that our biomimetic approach with *Drosophila* as a model has unique significance and potential in seeking promising technical seeds for the development of novel ICT technologies.

Identifying a decision-making circuit in the microbrain

We have been studying the mechanism of how courtship behavior is generated in *Drosophila* at the gene level and at the neuron level

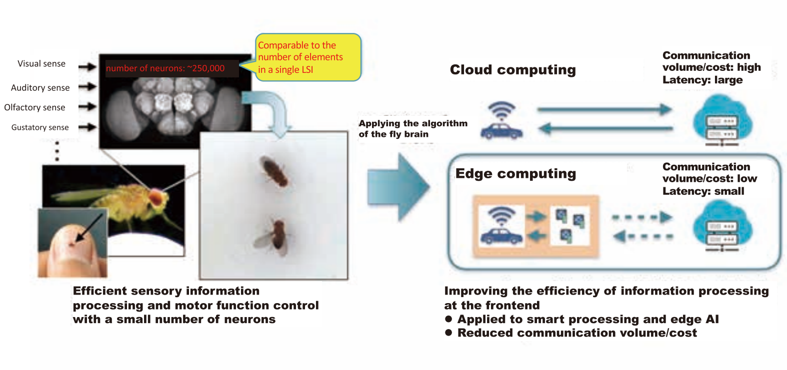


Figure 1　Features expected of a new information and communications technology mimicking the circuit properties of insect brains

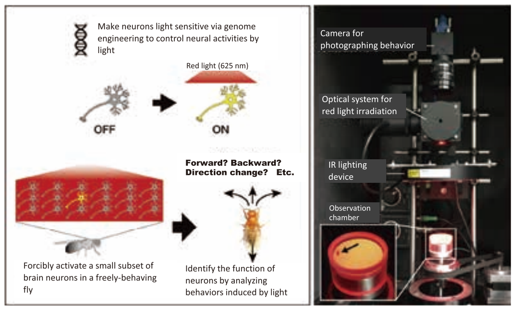


Figure 3　Experimental approach for identifying neurons that cause elemental movements forming a behavior
(Left) Schematic view for exploring neuron functions using an optical operation technique
(Right) Experimental device developed in-house

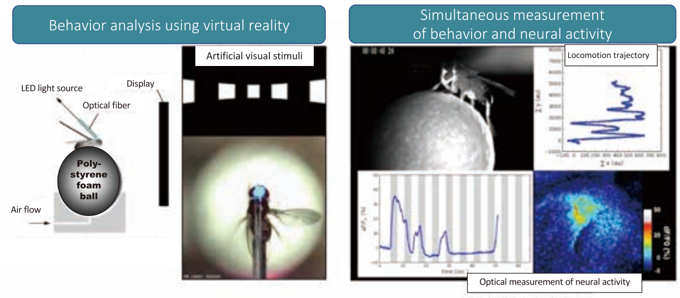


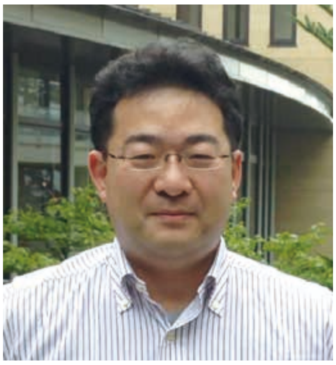
Figure 2　Our own techniques for artificially exciting neurons of a male individual subject placed on a treadmill to induce courtship behavior and record neuron activities in action on a real-time basis

for more than 30 years. Courtship is primarily an innate behavior, and therefore the behavior program (from detecting a courtship target to making decisions to start the courtship, assembling the elements of the behavior, and carrying it out) is written into the neural circuits created based on genetic information. We have found that a master control gene called *fruitless* plays a leading role in assembling the courtship circuits. The neurons whose shapes and properties are determined by the *fruitless* gene are collectively called the *fruitless* neurons. A comprehensive analysis of the brain anatomy has shown that the total number of *fruitless* neurons is about 2,000. Thus, identifying the *fruitless* gene has reduced the number of neurons to be analyzed from 250,000 to 2,000. We have succeeded in identifying a group of neurons that function as a “switch” to start the courtship behavior of the male through a multifaceted approach aided by genome editing, artificial activation and inhibition of select *fruitless* neurons, and activity imaging from these neurons. This group of neurons, called the P1 neuron group, consists of 20 (per brain hemisphere) male-specific *fruitless* neurons. The identification of the neuron group that works as the courtship switch has paved the way for studying the circuit structure and function underlying the decision-making process, and provided clues to understanding the circuit operation principle, which enables the microbrain to achieve highly efficient and timely input processing and output control. In the course of this study, we developed novel techniques for analyzing the brain activity and behavior of flies. One such technique is a behavior analysis system to induce courtship behavior under virtual reality conditions, i.e., all natural stimuli for courtship induction were replaced with artificial ones (Figure 2). Under natural conditions, once a male detects the female chemical cue pheromone, he starts to court and visually tracks the potential mate. In contrast, our flies carried P1 neurons that had been engineered to be photosensitive, and thus became sexually motivated when illuminated by light in the absence of any pheromone. Such motivated flies courted even toward an artificial visual pattern dissimilar to a real female, and the test male started to court in response to a moving stripe pattern shown on the computer screen. These artificial stimuli can be controlled very precisely unlike the natural stimuli emitted from live females. The development of this virtual reality experimental system enabled us to quantitatively analyze relationships between sensory input and motor output during male courtship. Furthermore, we have also succeeded in real-time measurement of neural activities generated within the male brain during courtship behavior by combining this technique with the neural activity imaging technique (Figure 2). Our virtual reality paradigm will be useful in the study of a wide range of behaviors other than courtship, and in fact has attracted significant interest among scientists in a vast variety of research fields.

Bridge to an information and communications technology

We are now focusing on tracking behavior, in which flies pursue other individuals guided by their visual sense. Going forward, we seek to clarify the details of the neural network that controls this behavior and aim to model its operating principle. As already described, a male homes in on a female as a courtship target mainly by its visual sense and chases the female, quickly adjusting its speed and travel direction along with the female’s movement. The male moves without wasteful motions, and never collides with the female even when it abruptly stops. To our surprise, the fly has just 1,600 facets, which make up the left and right compound eyes. What features does the brain of the fly extract from the visual input with this limited number of pixels? How does the fly use the extracted features to control motor function to achieve the agile and accurate tracking behavior? Our current challenge is to unravel these issues in the context of the function of the neural circuits. A first step is to draw the entire image of the neural circuits responsible for the sequence of information processing, from visual input processing to generating motor function output, with single-neuron resolution (Figure 3). Through this approach, we will determine how the insect brain, which has evolved under limited computational resources, precisely controls sophisticated behaviors. We expect that the “natural intelligence” we discover therein may be applied to drone control techniques and image information processing in small IoT devices.

R&D on Advanced ICT Devices at the Koganei Frontier Research Center



WATANABE Issei

Director of Terahertz ICT Device Laboratory, Koganei Frontier Research Center, Advanced ICT Research Institute

After completing doctoral course, he joined NICT in 2004. He has been engaged in research on millimeter- and terahertz-wave compound semiconductor electron devices and MMICs, and high-frequency measurement technologies. He is currently a Visiting Professor at Tokyo University of Science.
Ph.D. (Engineering).

HIGASHIWAKI Masataka

Director of Green ICT Device Laboratory, Koganei Frontier Research Center, Advanced ICT Research Institute

He received his Ph.D. in Engineering in 1998. After a two-year JSPS postdoctoral fellow, in 2000, he joined the Communications Research Laboratory (currently NICT). He has been engaged in research and development on wide bandgap semiconductor electron devices and thin-film epitaxial growth.
Ph.D. (Engineering).

The Koganei Frontier Research Center has been newly established under the Advanced ICT Research Institute with the NICT Headquarters (in Koganei, Tokyo) as its base. The three laboratories in this research center have been dealing with state-of-the-art technologies that open up frontiers in the ICT field. This article looks at some of the research being conducted by the Terahertz ICT Device Laboratory and the Green ICT Device Laboratory.

Terahertz ICT Device Laboratory—Opening up unused frequency bands

To mitigate the increasing shortage of frequencies and meet the demand for new spectrum, it is important to (1) use frequencies efficiently, (2) promote the shared use of frequencies, and (3) migrate to higher frequencies. As spectrum has become heavily used due to cell phones, smartphones, and Wi-Fi in (3) in particular, we are migrating wireless systems that use frequencies of 6 GHz or less to a high microwave band (under 30 GHz) where usage is lower, and developing technologies for opening up high-frequency bands such as millimeter- and terahertz-wave bands (30 GHz–3 THz; 1 THz = 1,000 GHz) which have not been fully used, as new radio wave and frequency resources (Figure 1). We are now researching and developing electronic/optical devices, integrated circuits, and systems that operate in frequency bands of 275 GHz or more where frequencies have not yet been allocated, aiming to bring forth next-generation wireless communication at 10 times or more the current rate, and to improve the performance of III-V compound semiconductor electron devices such as gallium nitride (GaN) channel transistors.

GaN is a wide bandgap* semiconductor and GaN-based electron devices can operate at high temperatures thanks to their higher heat conductivity and better heat dissipation than other substances such as silicon (Si) and gallium arsenide (GaAs) They also have a high electron saturation velocity and a high dielectric withstand voltage, and are expected to be applied as power electronic materials and devices with high output power and high breakdown voltage. To improve the performance of GaN-based transistors, it is indispensable to optimize the crystalline multilayer semiconductor structure and device structure; to optimize the fabrication process conditions; and to shorten the gate electrode length (L_g) and distance (L_{SD}) between the source and drain electrodes. Particularly, we are designing device structures with L_g of 100 nm or less (1 nm = 1/1,000,000,000 m), and the thicknesses of semiconductor layers and surface insulators with the accuracy of Å (1 Å = 1/10,000,000,000 m or 0.1 nm) and are actually fabricating GaN-based high electron mobility transistors (HEMTs) (Figure 2). As a result, we have achieved the highest maximum oscillation frequency (f_{max}) of 287 GHz in Japan, which is an index of the high-speed and high-frequency transistor characteristics. Concurrently, we have confirmed an output power density of 0.75 W/mm or more at a frequency of 70 GHz and output power performance that is seven times or more that of indium gallium arsenide (InGaAs) channel transistors made in NICT and whose f_{max} is 400 GHz or more.

Going forward, in order to utilize millimeter- and terahertz-wave bands in next-generation mobile communication systems after 5G and beyond (such as Beyond 5G/6G), we aim to raise the performance of compound semiconductor electron devices such as GaN-based HEMTs, integrate them with optical devices and antenna elements, and even develop a high-frequency measurement technique that can accurately measure the device performance and the transmission/reflection and dielectric characteristics of antenna radome materials and so on in the millimeter-

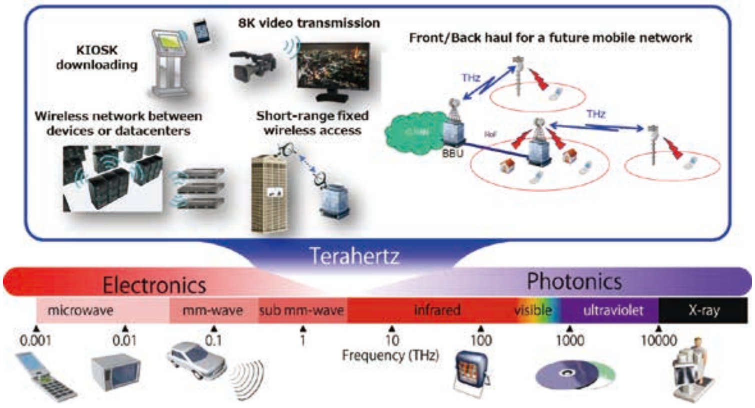


Figure 1 Overview of frequencies in millimeter- and terahertz-wave bands and their applications

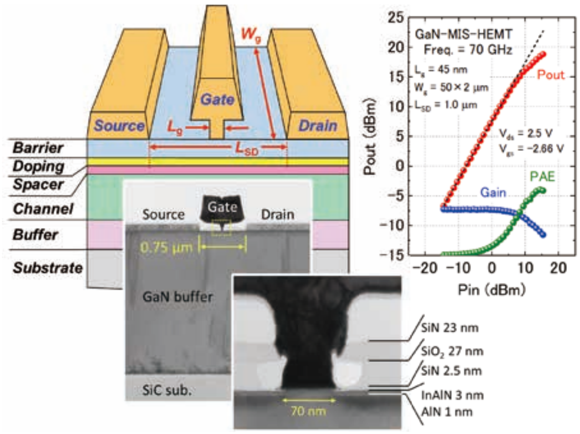


Figure 2 Schematic and cross-section of a high electron mobility transistor (HEMT) and its output power characteristics at 70 GHz

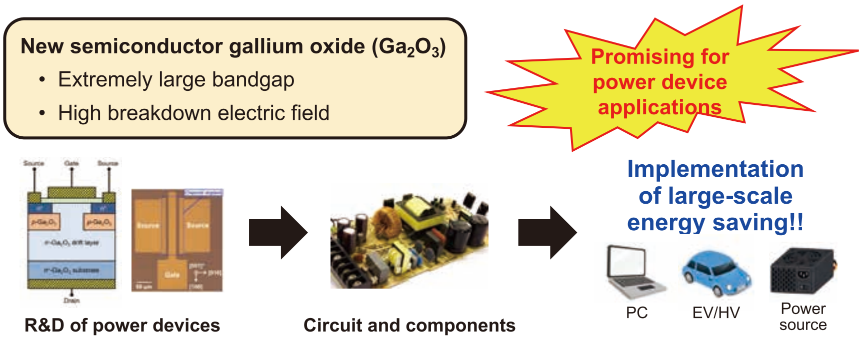


Figure 3 Characteristics of Ga_2O_3 and flow of its power device development

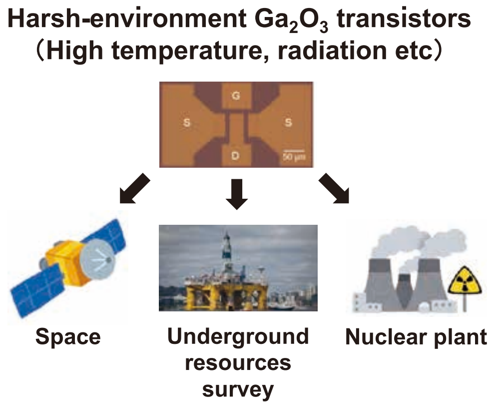


Figure 4 Application fields of harsh-environment Ga_2O_3 transistors

and terahertz-wave bands.

Green ICT Device Laboratory—The last 10 years' progress in research and development on gallium oxide devices

When we look back at the long history of research and development of semiconductor devices, we find that the following four steps were followed without exception:

(1) Discovery of a new semiconductor material
(2) Progress of crystal growth technology
(3) Development of devices that use the inherent physical properties of the semiconductor, and the various process/elemental technologies required to fabricate the devices
(4) Practical application of the devices, improvement of their performance for industrialization, development for mass production, and improvement of reliability, which are mainly undertaken by enterprises.

As many of the physical properties of semiconductors are determined by the most basic parameter called the bandgap, it can be said that a new semiconductor is one that has a different bandgap from any existing material. The development of new semiconductors may open up a new field of semiconductor electronics or elicit characteristics that far exceed those of existing semiconductor devices.

The Green ICT Device Laboratory conducts research and development on electronic devices using a new semiconductor gallium oxide (Ga_2O_3), which NICT discovered and succeeded in demonstrating its transistor operation ahead of other institutes in 2012. Ga_2O_3 has a very large bandgap of 4.5 eV; no other semiconductor has such a large bandgap. From the unique physical properties deriving from this outstanding bandgap, Ga_2O_3 is expected to be applied to power devices that save much energy thanks to the lower power losses in power conversion (Figure 3). In addition, the substance is expected to be suitable for ICT and signal processing devices in so-called "extreme environments" or "harsh environments" such as high temperature or high radiation where it is almost impossible to use normal semiconductors (Figure 4). This could also open up untapped areas for semiconductor electronics. Since reporting on the demonstration of Ga_2O_3 transistor action, its high potential as a semiconductor has attracted great attention, and now research and development on materials and devices is being actively conducted around the world. We have focused on research and development on the crystal growth required for device fabrication and the device process element technologies, and have been conducting milestone device demonstration as well as technology development for the last 10 years or so.

Research and development on Ga_2O_3 devices has now reached the stage of global competition, as evidenced by the start of multiple large-scale projects in the US, Europe, and Asian countries. We intend to continue demonstrating leadership as the pioneer in this field, and to conduct joint research and development with universities and companies at home and abroad to improve the Ga_2O_3 device technology and create a semiconductor industry originating in Japan.

*Bandgap: The degree of ease with which electric current (electron) flows. When the bandgap is small, the object becomes a semiconductor. A bigger bandgap results in a higher insulation or withstand voltage. The bandgap dictates the properties of semiconductor materials and devices.

Research Initiatives of CiNet under the 5th Medium- to Long-term Plan

Promotion of challenging studies for establishing the CiNet Brain

TAGUCHI Takahisa

Associate Director General, CiNet, Advanced ICT Research Institute

After working at Osaka University, he joined the Osaka Industrial Research Institute (currently Advanced Industrial Science and Technology (AIST)) in 1993, and was engaged in analyzing the dynamic state of a brain neuron network. After serving as Director General of AIST Kansai, he joined NICT in 2013 and led brain studies as such at CiNet. Doctor of Engineering.

OIWA Kazuhiro

Associate Director General, CiNet, Advanced ICT Research Institute

Joined the Communication Research Laboratory (currently NICT) in 1993. Since then, he has been engaged in research and development on single molecular measurement and molecular communication technology. Professor (joint appointment) of the graduate school of the University of Hyogo. He received the 23rd Osaka Science Prize, the Excellence Prize of the judging committee for Grants-in-Aid for Scientific Research in 2009, and the Science and Technology Prize Granted by the Minister of Education, Culture, Sports, Science and Technology in 2020. Ph.D. (Science).

This year, the Center for Information and Neural Networks (CiNet) celebrated the 10th anniversary of its founding. It was established in 2011 with the aim of connecting knowledge and information in research on human brain function to innovative applications of information and communications technology. It has previously developed a new technology for accurately measuring the functions and structure of the human brain, conducted research to clarify the information processing mechanism within the brain by measuring brain activity, and conducted research and development on network control technology, etc. based on the mechanism of the brain. In the 5th Medium- to Long-term Plan of NICT which started in April 2021, we will accelerate research on the functions of the human brain on the basis of accumulated technologies, knowledge and information, with the aim of attaining a human-centered ICT society as stated in Society5.0.

Research on brain information is the key to human-centered information and communications technology

To simply convey users' intentions, such as what they want to do or how they want to be, by speaking simple words, thinking, or just gesturing, to information devices, information and communications systems must be able to learn the required knowledge and information and think on their own to assist users. This skill requires the ability to understand context. To understand this ability, we have been conducting measurement and analysis on human brain activity involved in the higher brain functions (cognition, sensory reception, motor function, and even emotion) performed in the brain of a human as a sender and receiver of information. We are developing not only a decoding technology for reading and understanding the brain information from brain activity, but also an encoding technology for creating brain activity patterns from input stimuli. The results of these efforts will help achieve the ultimate communication; ICT that helps people fulfil their potential; and a society where people can feel true happiness and satisfaction.

The basis of this research is brain function measurement with a large-scale precision instrument that measures and analyzes precisely and from various angles the activities and structures of the brain involved in cognition, sensation, and motor control. In addition to making the existing fMRI measurement method (BOLD) more accurate, we are developing a technology to measure cerebral blood volume changes, etc. more directly reflecting neural activity by utilizing a biomarker different from BOLD. We intend to establish a technology to assess functions such as the olfactory sense, which is difficult to observe and is located deep in the brain. We are also developing a portable device for measuring brain activity in the living space, and we quickly feed back the research results to society. We are consolidating our analysis data into a database for utilizing brain activity data, which form the core of research on brain function in CiNet.

Improving human performance using analyzed brain information

Japan is a super-aging society and so there is an urgent need to maintain the motor functions of the limbs and body, as these affect healthy expectancy. To assess and improve the motor function of each individual, we have started building an emulator ("digital twin") that digitally reconstructs the motor function based on medical images and biological signals of the individual, and developing a system to provide support for behavior modification by using the emulator. We have clarified the development and deterioration of the inhibition mechanism that happens in the large-scale networks in the brain by acquiring fMRI functional images from brains that are executing sensation and motor function tasks from many persons of diverse age groups. Through such modeling, it is possible to maintain and im-

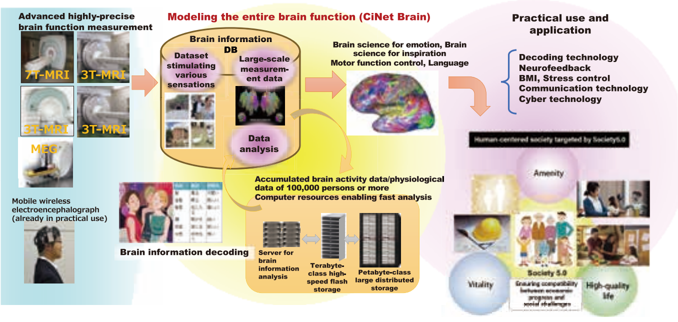


Figure 1 Overview of the brain function and neural network research and measurement system in CiNet
The highly-precise brain function measurement prompts the accumulation of brain information data and accelerates the construction of CiNet Brain and applied research on social implementation, based on the data.

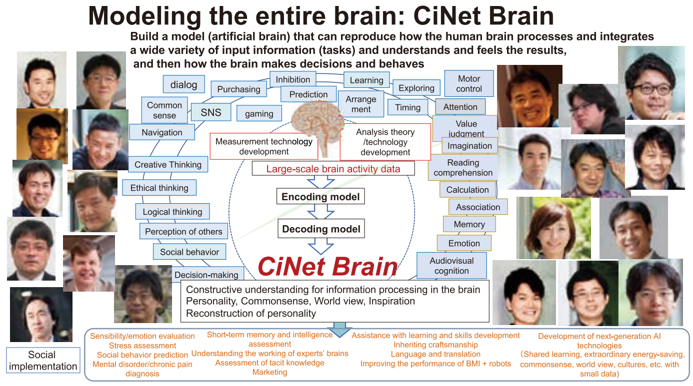


Figure 2 Research tasks for building CiNet Brain, and the researchers involved

prove the motor function ability. For example, people often experience deterioration of motor performance when placed under stress. We have clarified through fMRI experiments that activity in the dorsal cingulate cortex is involved. We have also shown that the deterioration of motor performance can be inhibited by applying transcranial magnetic simulation (TMS) to the dorsal cingulate cortex. Improving human performance in this manner is one of the major approaches used in brain information analysis research.

Decoding brain information and building an information processing model

We aim to build a model encompassing the entire information processing within the brain by analyzing the higher brain functions such as cognition, emotion, sensation, decision-making, motor control, sociability, and language of humans and unraveling the relationships among those functions. We call our information processing model that represents the bidirectional processing of decoding and encoding brain information "CiNet Brain." To build this model, we will measure brain activity under various conditions of sensation and cognition such as audio-visual stimuli, dialog, cognition issues, and VR environments, and will analyze brain functions such as cognition, emotion, and language. Some of the results are already being applied, and we are now working on objectively assessing the impressions and sensations of users toward products and services, by using the brain information read from brain activity in response to audio-visual stimuli.

The social brain network supporting the social interaction of humans in society

A decisive factor that distinguishes humans from other animals is the enormous society they have created and the sociability of human beings in society. Many of the various behavioral characteristics and issues of humans are formed within the context of "society." We have been collecting big data by combining SNS data that represents human social behaviors in the real world with fMRI data as well as enormous volumes of behavior data and personality and attribute data collected through online measurement. We advocate social brain science for the real world that mathematically analyzes the data, and are producing innovative results. We will apply this science to ICT technology that has high value for humans such as reducing mental stress and improving a sense of fulfillment in being alive and communications between individuals, and fulfilling potential ability by mathematically identifying emotion/decision-making mechanisms in actual society and improving mental health and decision-making in cyberspace as a routine activity.

Utilizing brain information and communications in real life: creation of high value-added information and next-generation BMI technology based on electroencephalogram and behavior data

With the aim of creating new ICT to achieve ultimate communication and fulfil human potential, we will also make brain–machine interface (BMI) technology more sophisticated. We are conducting research and development that will assist the reconstruction, prosthesis, and extension of physical functions, by upgrading infrastructure technologies such as a technology to fabricate biocompatible microelectrodes that can withstand long-term use within the brain and multipoint densification of the microelectrodes. We will also develop brain activity multimodal measurement technology, in- and out-body wireless communication technology, and a technology for decoding the intentions of motor function from brain activity.

In addition, we are building a model that provides high-value added information like mental state and potential such as interests and concerns, changes of feeling, motivation, and working memory, as well as interrelations between individuals. For this purpose, we developed a portable electroencephalograph and have acquired brain waves and behavior data involved in activities such as seeing, hearing, playing, learning, and working, in environments similar to real life from many people. We analyze the electroencephalogram and link the results to other biological information, subjective information, and so forth to determine the impressions and sensations of users toward information in the form of a technology that we can objectively assess.

Promotion of social acceptance of brain information and communications technology, and collaborative research among industry, university and government

For brain information and communications to be utilized responsibly as a next-generation ICT, this state-of-the-art technology must be socially accepted. We will consolidate researches and environments to improve such acceptance. We will proactively conduct collaborative research among industry, university and government on brain information and communications technology by strengthening collaboration not only with academic organizations such as universities, but also with industry groups.

For these purposes, we are encouraging the exchange of human and intellectual resources by conducting joint researches in collaboration with researchers and enterprises in various fields and accepting researchers, developing human resources and transferring technologies to enterprises. We aim to become a research and development base and to disseminate the results throughout society while refining scientific technologies and increasing social acceptance. We will develop brain information and communications technology to help create an ICT society where people can enjoy a good life in peace.

Terahertz Wave Wireless Communication Pioneered by Organic Electro-optic Polymers

KAJI Takahiro

Senior Researcher, Nano-Scale Functional Assembly ICT Laboratory, Kobe Frontier Research Center, Advanced ICT Research Institute, Ph.D. (Engineering).

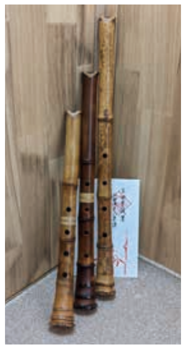
Biography

1981 Born in Kyoto prefecture.
2009 Completed graduate school's doctoral course (latter period) in Materials Engineering Science, Engineering Science, Osaka University.
2009 After serving as specially appointed assistant professor for Global COE (Core Research and Engineering of Advanced Materials-Interdisciplinary Education Center for Materials Science) in Engineering Science, joined NICT.
2015 Current position.

Research Activities

He is jointly conducting Research and Development for Expansion of Radio Wave Resources, which newly started in FY2021.

Q&As



Q What are you currently interested in outside of your research?

A I play Japanese traditional music ("honkyoku") with a five-holed bamboo Japanese flute ("shakuhachi"). My teacher encourages me to play in a certain style that is not written in the music scores, and I greatly enjoy it.

Q What advice would you like to pass on to people aspiring to be researchers?

A It is important to take an interest in a wide variety of research fields and to broaden your horizons. You should also try to challenge yourself by opening up untapped areas beyond existing research fields.

Q How do you spend your time on holidays?

A I enjoy taking my baby daughter, who was born in March, around the neighborhood. It is an immense pleasure to watch her growing each day.

In order to attain ultra-high-speed, large-capacity wireless communication in Beyond 5G, radio-over-fiber (RoF) technology is attracting attention. This transmits signal waveforms of terahertz waves (0.1–10 THz), which have higher frequencies than radio waves, as optical signals by using optical fibers. A RoF signal converter converts between optical and radio signals at each remote antenna. As terahertz waves have higher directionality than radio waves, the range covered by one remote antenna is limited and so a huge number of remote antennas are required. For this reason, high-performance, small, low-cost remote antenna transceivers need to be developed.

Existing remote antenna receivers using electronic technologies convert from terahertz to electrical signals, and then from electrical to optical signals by using an optical modulator. However, those receivers have problems such as complicated mechanisms, large device size, and high cost. We are focusing on organic electro-optic (EO) polymers that enable highly efficient optical modulation at ultra-high speeds above several hundred gigahertz. Our research aims to develop a radio-to-optical signal conversion device that can directly convert from terahertz to optical signals, without conversion to electrical signals.

To create such a device, we have developed our own technology for transferring EO polymer films on which poling (a process for aligning the directions of EO molecules) has been conducted in advance, and have used it to fabricate a device that combines EO polymers with terahertz wave low absorption loss materials, which would be difficult to fabricate by any existing method. With the fabricated device, we have succeeded in observing direct optical modulation by irradiating electromagnetic waves in the 100 GHz band.

We will continue improving the structure of the device in order to increase the radio frequency and optical modulation efficiency, and then work on its practical application.

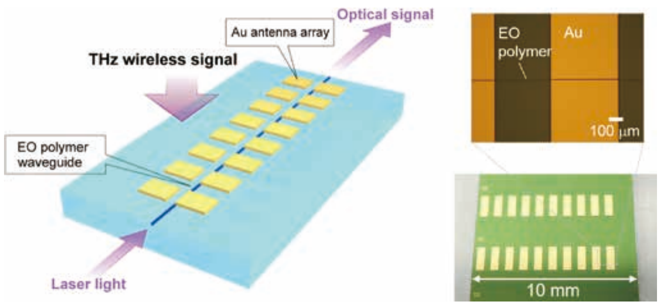


Figure Schematic diagram of radio-to-optical signal conversion device using EO polymer waveguides and Au antenna arrays, and a prototype 100 GHz-band device

On the Radio Wave Day and the Communications Promotion Month, the Award is given to individuals and entities who have contributed to the use of radio waves or the development of communication, and to persons who are expected to create outstanding digital contents.

* The affiliations and positions are those at the time of winning the awards.

Awards for FY2021 Radio Day and Info-communications Promotion Month

Awards for Minister of Internal Affairs and Communications Award (Group)

Kashima Space Technology Center, NICT

● Date: June 1, 2020

● Awarded for: Long-time utilization of the Kashima 34-m parabolic antenna as an observation station of Japan, participating in many international projects, including measuring the movements of the Pacific plate with very long baseline interferometry, and greatly contributing to the research and development of infrastructural technologies using radio waves and transferring them to research organizations in Japan and abroad.

● Receiver's comment: We feel greatly honored to receive this award. The 34-m parabolic antenna was dismantled in fiscal 2020, but NICT will continue to spread and promote VLBI technology transfer to other organizations, in addition to participating in the IVS observation project.
We will conduct research and development in new fields of satellite communication at Kashima Space Technology Center, such as the development of Engineering Test Satelite-9.

Awards for FY2020 Radio Day and Info-communications Promotion Month SHIDA Rinzaburo Award (Personal)

SASAKI Masahide

Director General, Quantum ICT Collaboration Center, NICT

● Date: June 1, 2020

● Awarded for: Leading activities such as research and development on quantum cryptographic communication technology for many years, dedicating himself to establishing world-class technologies and their global standardization, and greatly contributing to the development of the quantum cryptographic communication technology field in Japan.

● Receiver's comment: It is a great honor and privilege to be selected for this prize. I deeply thank my many colleagues and persons concerned for their great support which helped me win this award, on behalf of the industry-academia-government collaborative team I have been working with. Motivated by this prize, I will continue working on advanced research and development.

In the Tokyo 2020 Olympics torch relay, Mr. YOSHIDA Shinichi* participated in the lighting ceremony as a torch runner of Koganei city, in the fourth leg on the sixth day in Tokyo.

*Japan national para table tennis player (Male, class 3) in Rio de Janeiro Paralympics 2016

On each leg scheduled for the day, each torch runner lit the next runner's torch in a "kiss" in front of the stage.
In this ceremony, he offered the sacred fire to the sacred fire dish as the torch runner on the last leg.

July 14 (Wed), 2021
at Tokyo Racecourse

NICT NEWS 2021 No.5 Vol.489
Published by **Public Relations Department, National Institute of Information and Communications Technology**
Issue date: Sept. 2021 (bimonthly)

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ISSN 2187-4050 (Online)