# NICT NEWS

NICT National Institute of Information and Communications Technology

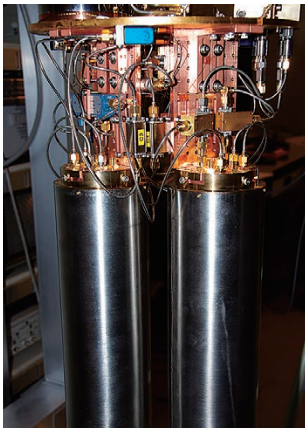
No.465 AUG 2017

FEATURE

## Paving the Way for the Information and Communications Technology

NICT NEWS No.465 AUG 2017
National Institute of Information and Communications Technology

# CONTENTS





**Cover photo: "Microwave measurement system for superconducting quantum circuits, incorporating dilution refrigerator"**

A microwave measurement system used to explain new superconducting artificial atom and photon states. Several microwave coaxial cables can be seen. To suppress thermal excitation in the item being measured and make a precise measurement on the order of a single microwave photon, the superconducting quantum circuit device is cooled by thermal contact with the minimal temperature plate (approx. 10 mK) of a dilution refrigerator.
The superconducting quantum circuit is extremely sensitive to magnetic noise so, as shown in the photo in the upper left of this page, it is installed inside a two-layer magnetic shield (silver colored cylinders) which attenuates external magnetic field fluctuations by a factor of 1/1000 (fabricated in collaboration with NICT's Radio Wave Management and Prototype Development Group).

INTERVIEW

# Establishing Advanced Technologies beyond Extensions to Current Systems

**Iwao HOSAKO**
Director General
Advanced ICT Research Institute

After completing a doctoral program, Iwao HOSAKO worked for NKK Ltd. (currently JFE). In 1996, he joined the Communications Research Laboratory, Ministry of Posts and Telecommunications (currently NICT). He has been engaged in research and development of terahertz semiconductor devices and various application systems.
Ph. D. (Science).

**ICT technology is currently producing remarkable developments. However, many issues that are difficult to resolve are manifesting with current technology such as increasing costs due to the explosive increase in data volume and increasingly complex security and control. The Advanced ICT Research Institute takes a long-term perspective conducting R&D to address these issues using innovative ICT technologies. We spoke with Dr. Iwao HOSAKO, Director General of the Institute, regarding the many advanced research fields they are dealing with at their two locations, in Kobe and in Koganei (Tokyo).**

## Playing pieces strategically for the long game

**— My image of the Advanced ICT Research Institute is that it is cultivating new technologies for the future. Can you talk about what sorts of systems and what research fields you are working on?**

**HOSAKO:** Broadly speaking, research at the Advanced ICT Research Institute is composed of one laboratory, the "Frontier Research Laboratory," and three centers, the "Quantum ICT Advanced Development Center," the "Green ICT Device Advanced Development Center," and the "DUV ICT Device Advanced Development Center."

These Centers handle fields that are relatively close to being realized in society, or will be in the foreseeable future. Of course, they are part of the Advanced ICT Research Institute, and as such, these technologies will still take some time before they are fully deployed on a global scale. Even so, research results are steadily accumulating, and the desire for some of these technologies is growing. One such example is quantum cryptography, which will bring revolutionary advances that are urgently needed in information security. Our three development centers are dedicated to making progress in these advanced fields.

On the other hand, the Frontier Research Laboratory handles themes that look farther into the future than the Centers do. There are many projects, but most of them are in the research areas of bio-ICT, nano-ICT, superconduction, and ultra-high frequency. Not all of these projects will necessarily be successful in the future, but the themes have potential to bring great change that will revolutionize the world. They are important, and truly at the frontiers of technology.

Our research is also advanced in terms of scholarship, with approximately 35% of all R&D related NICT press releases coming from the Advanced ICT Research Institute in FY2016. The Advanced ICT Research Institute also accounted for 20 to 25% of academic papers from NICT in the same period.

**— So your mission is to always look for the "seeds" of new technologies and to cultivate them, isn't it?**

**HOSAKO:** Around 30 years ago, Japan was criticized as a "basic research free-rider," meaning that all we did was use basic research from overseas to do applied research and develop products. Since then Japan, including research by private enterprise, has focused activities more and more on basic research. Even NICT's predecessor, the Communications Research Laboratories (CRL) demonstrated advanced basic research. By attracting excellent personnel and finding important themes for the future, they established the Kansai laboratory in 1989, which became the foundation of the Advanced ICT Research Institute of today.

Many of the research targets set at the time have developed, expanded, and moved to other organizations. Examples include the natural language translation research currently being done at Keihanna Science City and brain networks and communications research being done in the center jointly operated with Osaka University. We expect that many results will grow out of the Advanced ICT Research Institute in the same way in the future.

We do not expect all of the research we are working on to be useful on a global scale, but if even one result has a large impact and grows into a large research field in 20 or 30 years, we will be able to look back and see the value of the Advanced ICT Research Institute.

INTERVIEW

# Establishing Advanced Technologies beyond Extensions to Current Systems

## Having a strong impact in both device engineering and biotechnology

**— What particular research subjects are you focusing on in these two promising fields for the future?**

**HOSAKO:** There are some themes that we believe will have an especially large impact on society in the future.

Information and communication deals with communication between nodes, but it is important to consider not just the communication part, but also the information processing part. Till now, information processing hardware has developed according to Moore's Law,* describing the miniaturization of circuits and increases in performance. However, we are nearing the limits of conventional development and a time when we will have to utilize entirely new principles. We believe that various technologies being cultivated at the Advanced ICT Research Institute may be very applicable to this issue.

One such technology is in device engineering. The Advanced ICT Research Institute is pursuing R&D on various types of devices using optical, electronic, and superconducting technologies. Several candidates have surfaced to answer the question of which will be the best for next generation devices. These are footholds to providing new material in fields like computer engineering and computer science.

Another area is that of bio-technology. Currently there is much attention on Deep Learning approaches, which use neural networks with multi-layer structure (modeling neural network structures in the human brain), and this is producing real results. This originated from a biological perspective, initially learning from the overlapping layers and states of nerve structures, but even now it cannot be said that these principles are fully understood. We take an approach based on understanding, and believe that this type of approach is possible. There are several information processing mechanisms involved in biology, and if we can explain each of them, we should be able to accomplish some very interesting things.

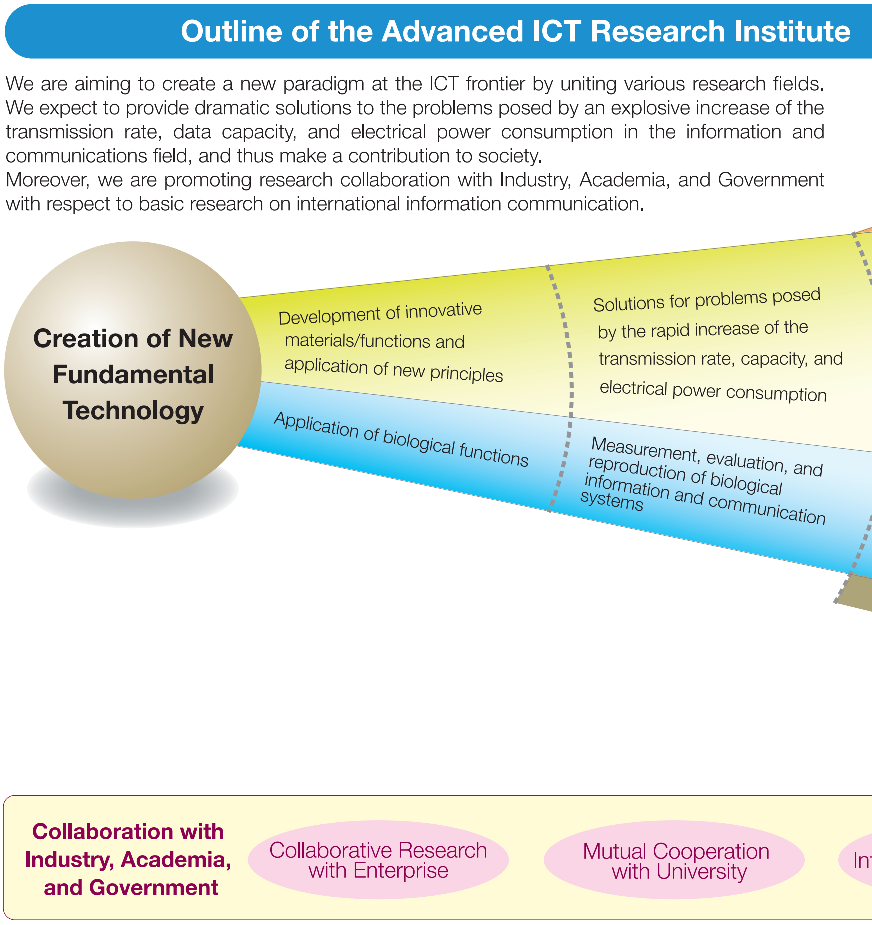



Figure Overview of the Advanced ICT Research Institute

One example is analysis of insect brains, which is just getting started. The brain of a fruit fly has approximately 200,000 neurons. That is five orders of magnitude smaller than the case of the human brain, with its tens to hundreds of billions of neurons, but it still has very advanced functionality. If we can understand how it works from basic principles, we will be able to build some extremely interesting and useful systems.

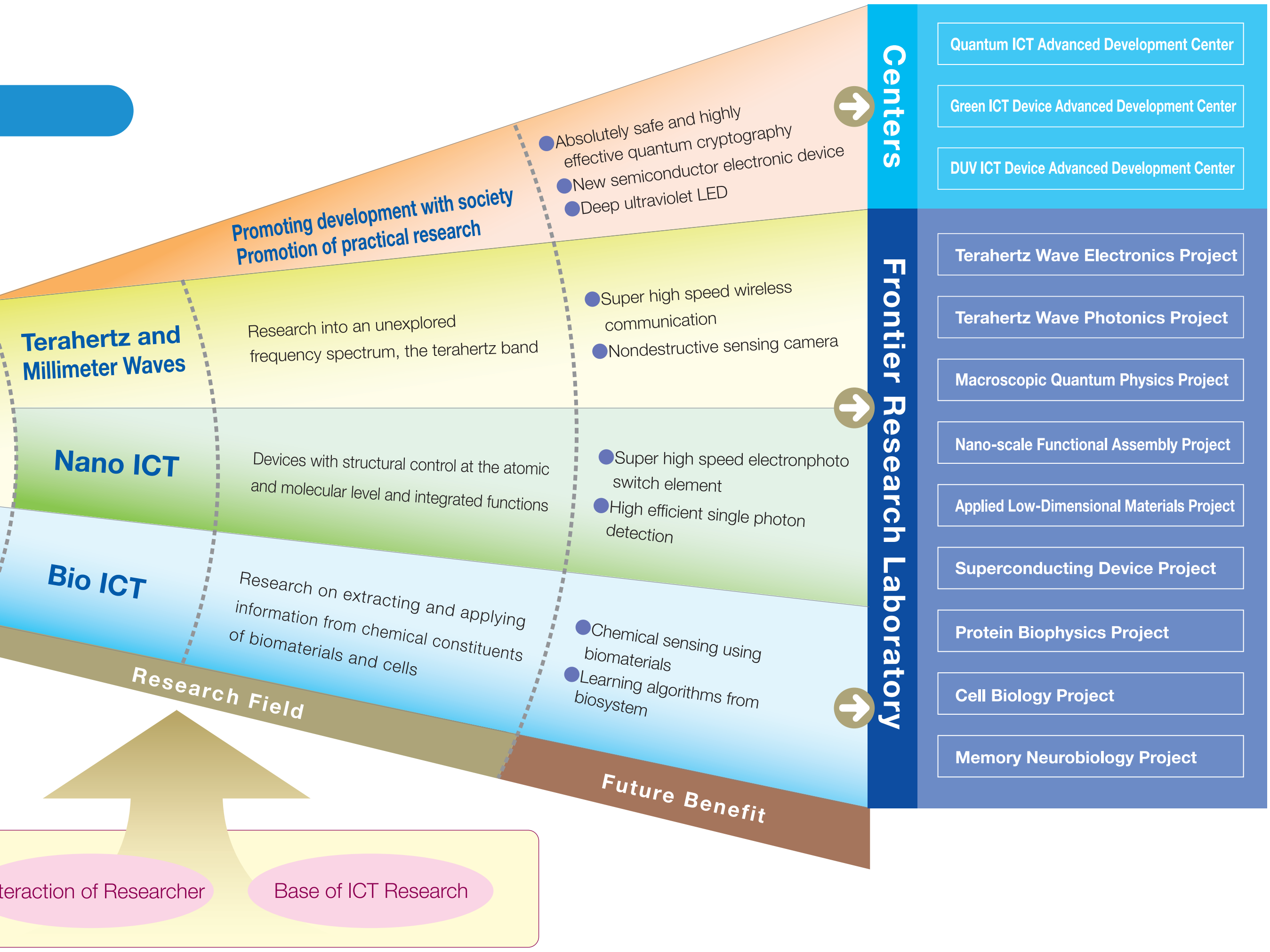
Till now, biotechnology has been focused mainly in fields such as medicine and pharmacology, but in the future we see it more and more as an area to learn from in engineering as well.

## Finding ways to integrate the ideas of individuals into our mission

**— The Advanced ICT Research Institute has locations in Kobe and in Koganei. How are roles divided among them? And how do you decide on research themes in anticipation of the future?**

**HOSAKO:** Major themes are divided, with

* Moore's law
Moore's law is the observation that the number of components per integrated circuit doubles every year. This law was described by Gordon Moore in 1965. Gordon was a cofounder of Intel, a semiconductor manufacturer in the United States.




nano-ICT and bio-ICT in Kobe and ultra-high frequency and quantum ICT in Koganei, but rather than segregating them that way, it is more just a matter of where the people involved are located.

Most of the themes at the Advanced ICT Research Institute are based on ideas from individual researchers. We look far into the future, considering various ideas and which ones will become important. In this process, we cannot overlook any ideas from individuals. This approach is quite unique to the Advanced ICT Research Institute, even within NICT, but it does not mean we simply follow our own research interests. NICT is still ultimately committed to mission-based research. Our resources are also by no means large, with a total of fewer than 200 researchers in both locations. Of course we need to select and focus our efforts.

That said, selection and focus at the Advanced ICT Research Institute is characterized more by asking "What sort of future will we work towards?" rather than simply, "Do this! Don't do that!" This helps to align the directions of researchers, naturally focusing resources so that we can produce a strong impact, even with limited resources. I feel that pointing out these directions is also part of my role as the Director General of the Institute.

# 'Molecular State' of Artificial Atom and Photons

## New tool for quantum information technology

**Kouichi SEMBA**
Executive Researcher
Frontier Research Laboratory
Advanced ICT Research Institute

Prior to joining NICT in 2013, Kouichi SEMBA engaged in research on superconducting quantum electronics at NTT Basic Research Laboratories, NTT Corporation, and at the Global Research Center for Quantum Information Science of the National Institute of Informatics. He is the Principal Investigator of the Macroscopic Quantum Physics Project. Ph.D. (Engineering).

**Fumiki YOSHIHARA**
Senior Researcher
Frontier Research Laboratory
Advanced ICT Research Institute

**Tomoko FUSE**
Senior Researcher
Frontier Research Laboratory
Advanced ICT Research Institute

**This research began from asking the basic question,"What would happen if coupling between light and an atom was made extremely strong?" We have realized *extremely strong* coupling using a superconducting artificial atom, which has similar quantum properties to atoms, and microwave photons in a superconducting circuit. We then found some very interesting molecule-like states (ground states) in the artificial atom and photon.**

### Matter-light interaction and quantum nature

In modern life, we make use of coupling between matter and light everywhere, in lasers and other devices. The blue light emitting diode, which led to the 2014 Nobel Prize in Physics, is one such example. We also often hear the word "quantum." One example is how, as laser light is made very weak, the nature of photons (light quanta) begins to appear. Also, we eventually reach atoms as matter is divided smaller and smaller, and the energy of electrons is known to be discrete (quantized) within atoms. Using this unique quantum nature of photons and electrons, future ICT technologies based on completely different principles have been conceived, such as quantum communication and quantum cryptography, and NICT is conducting research in fields related to these.

The Macroscopic Quantum Physics Project was started in 2014 as part of this, and it has used superconducting circuits to conduct research on the quantum properties of interactions between light and matter. Superconducting circuits can be fabricated using semiconductor micro-fabrication technologies, so a variety of physical systems can be designed on small chips that are only millimeters across.

### Interaction between superconducting artificial atom and photons in microwave LC oscillators

In this research, we have designed a circuit using a superconducting magnetic flux quantum bit (qubit) —which is also called an artificial atom because, like an atom, it has discrete energy levels — and a photon inside a microwave LC oscillator, such that they have deep strong interactions (Figure 1). The state of superconducting flux qubit is a macroscopic electrical current state with many electrons flowing in a superconducting loop, so it produces a magnetic dipole moment that is orders of magnitude larger than that from the micro-electrical current state of electrons in an atom. Also, by using an LC oscillator designed to increase the zero-point fluctuation current, which is based on the uncertainty principle in quantum me-

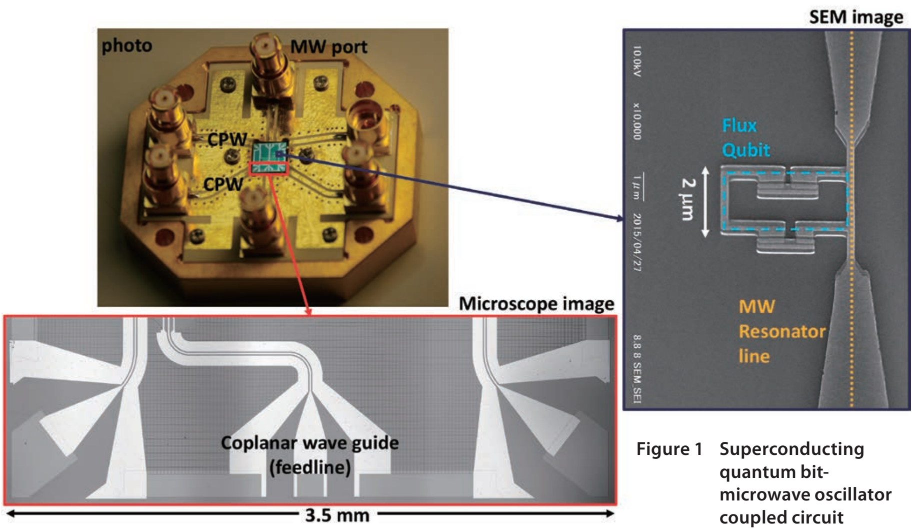



Figure 1 Superconducting quantum bit-microwave oscillator coupled circuit

References
1. F. Yoshihara, T. Fuse, S. Ashhab, K. Kakuyanagi, S. Saito and K. Semba, "Superconducting qubit–oscillator circuit beyond the ultrastrong-coupling regime," Nature Physics 13, 44 (2017).
2. T. Fuse, F. Yoshihara, K. Kakuyanagi, K. Semba, "Superconducting artificial atom and electromagnetic field interaction—beyond strong coupling—," to be published in the Nihon Butsuri Gakkaishi (Butsuri) Journal of the Physical Society of Japan.

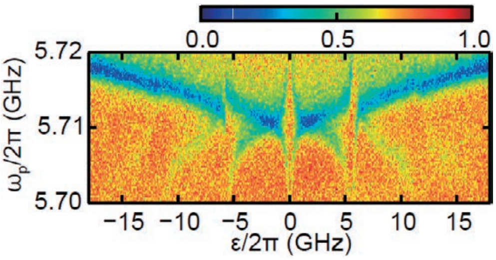



**Figure 2 Transition spectra of deep strong coupling circuit (masquerade mask pattern*) Horizontal axis is the magnetic flux bias energy of superconducting quantum bit , shown by frequency, and the vertical axis is the transmission microwave frequency.**

* So named because of similarity to mask shapes in Venice's Masquerade Carnival.

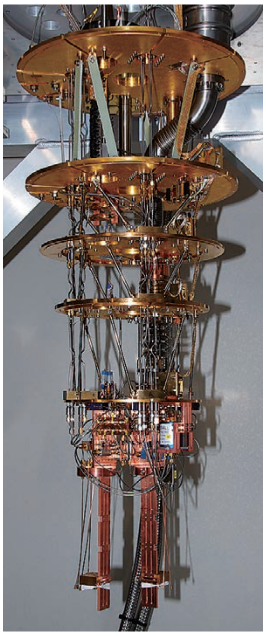


**Figure 3 Dilution refrigerator (reaching temperatures near 20 mK) The lower 350 mm fabricated in collaboration with NICT's Radio Wave Management and Prototype Development Group**

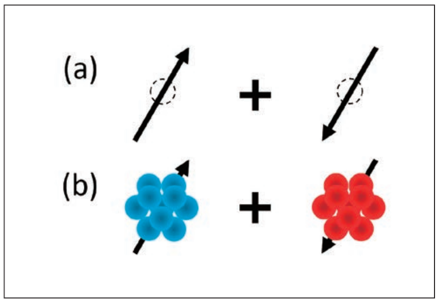



**Figure 4 Schematic ground state of atom-photon circuit under (a) no coupling, (b) deep strong coupling**

chanics, we were able to realize for the first time a deep strong coupling state in which the interaction energy between the quantum bit and microwave photon exceeded the transition energy of quantum bit or microwave photon itself. We also successfully measured the absorption spectra of the state (Figure 2). A dilution refrigerator was used in the measurements to cool the sample to approximately 20 mK, so that the absorption of a single microwave photon could be discriminated (Figure 3).

## Deep strong coupling

So, what can happen in a deep strong coupling regime? Consider the ground state (lowest energy state) of an atom-photon coupled system. When there is no coupling between atom and photon, their states can be considered independently.

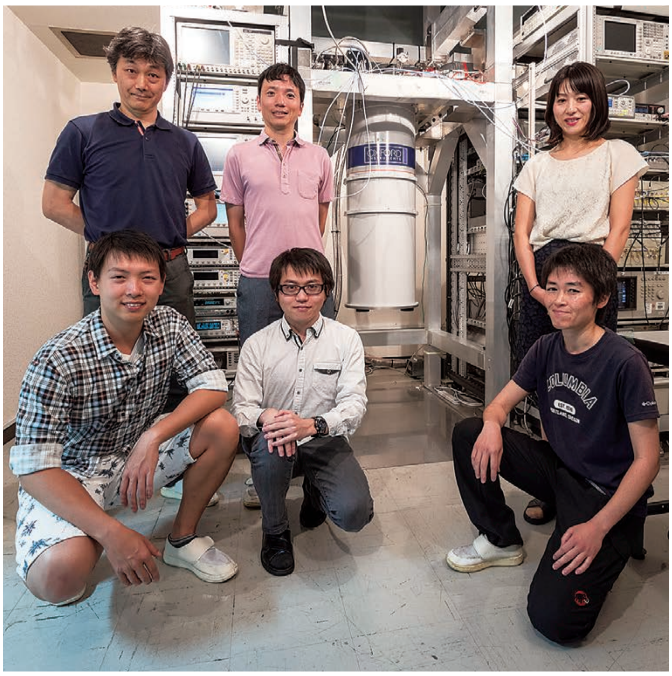
Individual photons have energy, so no photons are in a ground state. The ground state of an atom is expressed when the atom's up-spin and down-spin are superimposed (spin is the direction of magnetic moment) (Figure 4(a)). When coupling increases into the deep strong coupling regime, the ground state, the blue-photon-dressed states* of spin up and red-photon-dressed state* of spin down are superimposed (Figure 4(b)). In other words, rather than there being no photons in the ground state, when the atom is spin up, the photons always take on blue, and when they are spin down, they always take on red. Thus, there is strong correlation between the atomic states and photons, and this superposition state (quantum entanglement between atom and photon; similar to the Schrödinger's cat-like state) is the ground state.

Generally, quantum entangled states are quite fragile, but the quantum entangled ground state generated in deep strong coupling is not excited states, so this state can be expected to be much more stable.

## Conclusion

Quantum entanglement is an important resource for quantum information processing and quantum ICT, and recent expansion into basic science and measurement applications is promising, including attempts to apply multi-photon entangled states for quantum enhanced sensing. Deep strong coupling states have just been discovered, but there is on-going research on applications of such "Schrödinger's cat" states in quantum information processing and quantum enhanced sensing. Interested persons can refer to the original paper[1] or the explanatory article in Japanese.[2]

* Spin dresses phase-aligned virtual photons. Taking spin-up dressed photons as having phase of 0 (shown in blue), spin-down dressed photons will have phase of $\pi$ (shown in red).



**Project members**
**Front row from the left: Ziqiao AO (collaborating researcher), Yuya YONEZU (collaborating researcher), Tomoko FUSE (Senior Researcher)**
**Back row from the left: Kouichi SEMBA, Fumiki YOSHIHARA (Senior Researcher), Akiko HOSHI**

# Spontaneous Formation of a Globally Connected Contractile Network in a Microtubule-motor System

**Takayuki TORISAWA**
Researcher
Frontier Research Laboratory
Advanced ICT Research Institute

After receiving Ph. D. degree in 2014, Takayuki TORISAWA joined NICT. Since then, he has been engaged in research on the regulatory mechanisms of molecular motors, collective motion, and self-organization in motor-cytoskeleton systems. CREST Researcher (Creation of Fundamental Technologies for Understanding and Control of Biosystem Dynamics). Ph. D. (Arts and Sciences).

**We have discovered various networks formed by microtubules, a kind of cytoskeletal protein, and kinesin, a molecular motor operating on them, and the ability of these networks to cause an overall contraction. We have also created mathematical models able to explain their dynamics quantitatively. Simulating cytoskeleton dynamics in vitro (in a test tube) and in silico (in a computer) is promising for development of technology to change cell function and cell organizational structure more easily.**

## Various structures and dynamics observed within cells

Living things are all composed of cells. Cells move and change their shape dynamically in response to external stimuli and perform various biological activities. These dynamic changes in cell structure are accomplished by the cytoskeleton, including actin protein filaments and microtubules, and various proteins that connect them (Figure 1A). The cytoskeleton produces changes by changing shape and length of filaments through polymerization and depolymerization, and also through movement of proteins connecting the filaments. Well known major cytoskeletal functions include material transport rails inside the cell, and the mitotic spindles (microtubules) and contractile ring (actin) that form during cell division (Figure 1B). Besides these, plant cells, muscle cells (myocytes), and tracheal epithelial cells have mesh-like network structures of microtubules that work to maintain the shape of the cells (Figure 1C). There has been very little previous research on the formation of such networks and their dynamics relative to research on structures such as the mitotic spindle. As such, the goal of this research has been to explain the mechanisms of dynamics in these sorts of network structures.

## Various network dynamics emergent by combining two types of element

Inside real cells, many proteins interact with each other to bring about complex biological phenomena. One way to identify the elements and properties needed for a given complex phenomenon is to reconstruct a coarse-grained system. More concretely, a simple system composed of a few elements that are expected to be needed is prepared and then comprehensively observed and modeled to gain a deeper understanding. In this research, we built a system to understand the dynamics of cytoskeletal network structures consisting of only microtubules and a type of protein molecular motor called kinesin. There are many types of kinesin, and 45 types of kinesin genes in humans. We used a type called kinesin-5. Kinesin-5 has four motor domains (which connect with microtubules and are the primary parts handling mobility), and can form network shapes by bundling multiple microtubules. By moving along the microtubules, they also cause sliding motion among the microtubules within a bundle, causing dynamic

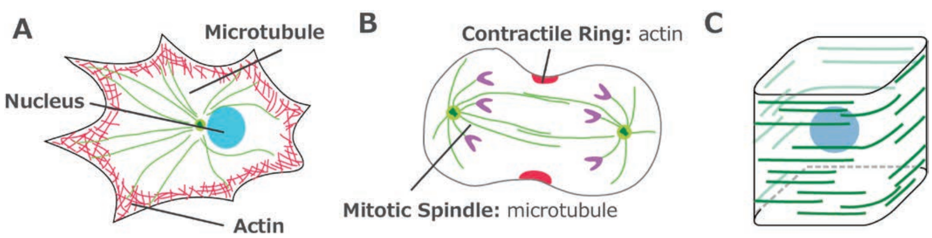



Figure 1 Various structures created in a cytoskeleton and their movement
A: Cytoskeleton in an animal cell (actin and microtubule) in interphase
B: Cytoskeleton in a somatic cell when it is dividing
C: Microtubule network observed in plant cells

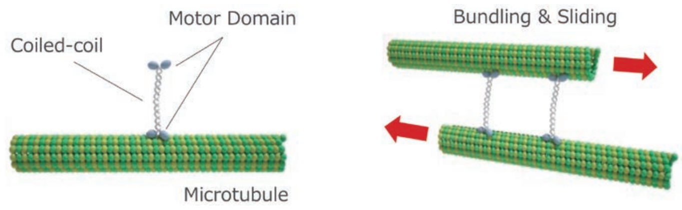



**Figure 2** Molecular motor used in experiments (kinesin-5); structure and function

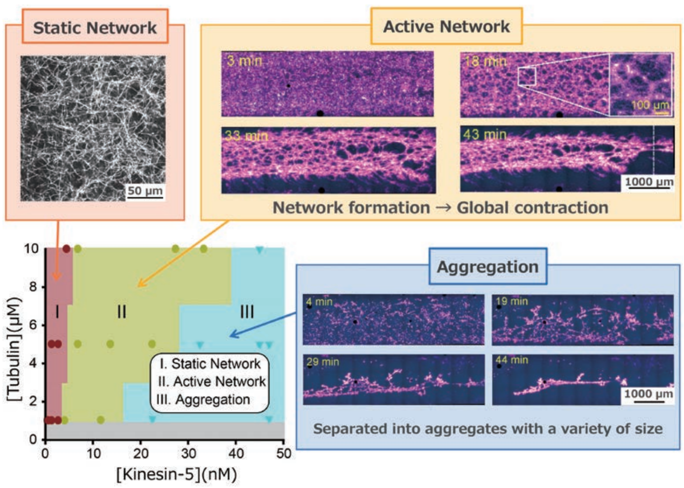



**Figure 3** Various patterns created by kinesin-microtubule mixed system and a graph showing their dependency on density of elements

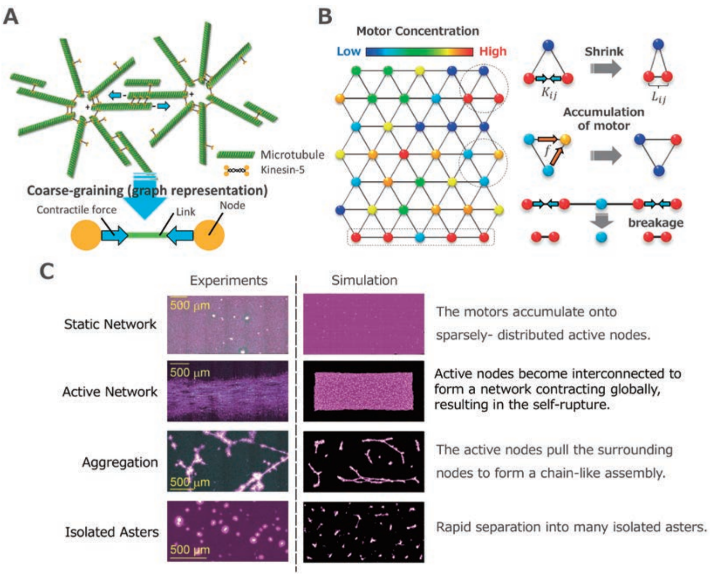



**Figure 4** Mathematical model overview and comparison with experimental results
A: Network coarse-graining
B: Three localized rules in the model
C: Comparison between experimental results and simulation

changes in the network (Figure 2). We mixed kinesin-5 and microtubules in various concentrations and conducted comprehensive observations of the resulting dynamics (Figure 3). Figure 3 shows that when kinesin-5 concentration is low, networks are formed but there is no change to the overall structure (static network). As the concentration of kinesin-5 is increased, microtubule networks slowly start to contract after they form. Soon some begin to break, and a transition to a sudden contraction occurs (active network). If kinesin-5 concentration is increased further, there are localized strong contractions and division into clusters of various sizes (aggregation). These sorts of network contraction depend on motor concentration and mechanical characteristics, and we confirmed that by changing the motor properties, small radially extended microtubule structures (asters) distributed uniformly over the whole observation area formed.

## Creating mathematical models to explain network dynamics

Based on our comprehensive observations of network dynamics in systems combining kinesin and microtubules, we constructed a coarse-grained model to identify the essential elements of the phenomena. The theoretical model was built in collaboration with the group of Associate Professor Shuji ISHIHARA of the Science and Technology Department of Meiji University (currently Associate Professor at The University of Tokyo), and we were able to reproduce the observed experimental results (static network, active network, aggregation, and aster formation) with a network model specifying only three local rules (Figure 4). It also showed great promise in predicting the effects of changing motor characteristics on network structure.

## Future prospects

Cytoskeleton dynamics affect not only cell shape and behavior; they also affect the shape and function of tissues, which are groups of cells. We were able to show the potential for great changes in cytoskeleton dynamics by changing only concentrations and motor characteristics in simple systems consisting of only two types of protein. By successfully modeling it mathematically, we also hope to contribute to technical developments that enable cell function and structure to be changed more easily.

# Re-design of Biomolecular Motors Reveals Mechanisms Generating Directional Motion under Thermal Agitation

**Ken'ya FURUTA**
**Senior Researcher**
**Frontier Research Laboratory**
**Advanced ICT Research Institute**

After completing graduate school, Ken'ya FURUTA became a Research Fellow of the Japan Society for the Promotion of Science, and then joined NICT in 2009. Senior Researcher since 2013. Engaged in research on design and fabrication of protein nanomachines. Ph.D. (Arts and Sciences).

**The Frontier Research Laboratory has, for the first time, successfully created artificially designed new biomolecular motors. These new motors were implemented based on dynein,*1 a type of biomolecular motor, fused with another functional module also existing in nature. We were also able to fabricate molecular motors that move in the opposite direction. These results are very promising for use as a design principle for artificial molecular machines that function efficiently in the presence of vigorous thermal agitation, which is unavoidable at the nanometer scale.**

## Background

A young genius gathers countless "Microbots" together to create a large structure which moves around the town freely. Such a scenario appeared in the computer animation movie Big Hero 6, released in 2014, and it shows how small machines that can only perform simple movements on their own can be made to perform large, complex tasks when gathered together. This idea has often been depicted as the future of artificial machines.

## What are molecular machines?

This sort of idea is becoming a major trend in the world of science and technology. In fact, the 2016 Nobel Prize in Chemistry was awarded for research implementing nanometer scale switches and bearings using organic molecules and chemical synthesis technology and producing work and power by manipulating extremely small molecules. This type of technology is still at the basic research stages, but it has potential for huge impact on real society in the future.

Since the industrial revolution, artificial machines have been made with great success based on a paradigm of correct operation through top-down control systems. However, much attention has recently been placed on the search for algorithms used by living organisms. For example, there is much activity developing new machines with many elements performing distributed processing, taking hints from the way trees change their shape adaptively, and from the autonomous distributed systems of ants (McEvoy et al., Science 2015, etc.). Existing top-down networks are showing weakness after weakness, such as vulnerability to pin-point attacks and the difficulty in making large-scale changes to networks, the bottom-up survival strategies from biology used in these systems provide a good counter-proposal for consideration.

## Life already has extremely functional molecular machines

In living organisms, there are systems at all levels that very naturally perform incredibly advanced distributed processing from a human perspective, from the level of ant societies, to individuals, biological tissues, and down to the cell level. At the cell level, most muscle, spindle, cilia and flagella cells, have nanometer scale molecular machines made of proteins, called biomolecular motors, that work on filaments extending throughout the cells. These produce cooperative phenomena such as contraction, elongation, and oscillatory motion on a scale of a centimeter or more, six to eight orders of magnitude larger than the motors

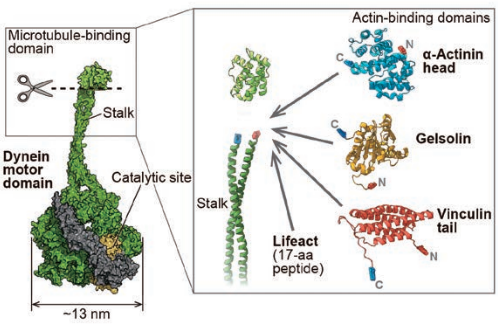



**Figure 1** Newly designed biological molecular motor. The microtubule binding site is removed from dynein, and an actin-binding site is combined with the dynein motor domain.

Terminology

*1 Dynein
A type of biomolecular motor that works inside cells. It is a protein complex that moves along microtubules featuring a clear modular structure, with a ring-shaped motor domain and a microtubule bonding site that protrudes from the ring.

*2 ATP hydrolysis activity
Biomolecular motors such as dynein use adenosine triphosphate (ATP), which serves as the energy currency in cells, as the driving force. The major structural changes accompanying hydrolysis of ATP is very important for unidirectional motion.

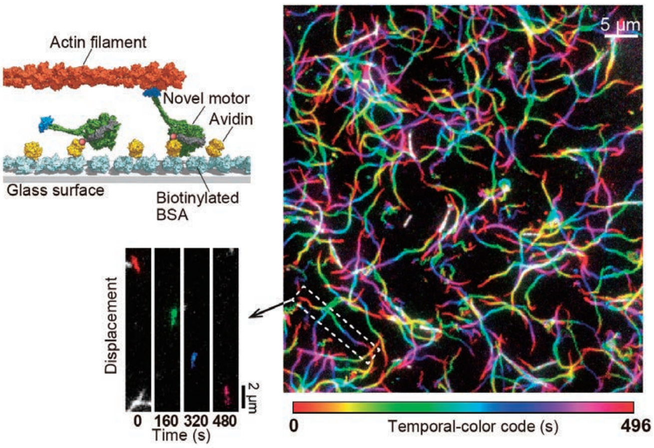



**Figure 2** **Total internal reflection fluorescence microscope image of the new molecular motor fixed to a glass surface. How actin filaments are moved is shown. The video is processed, with a different color applied to actin filaments for each time frame to show motion of the filaments.**

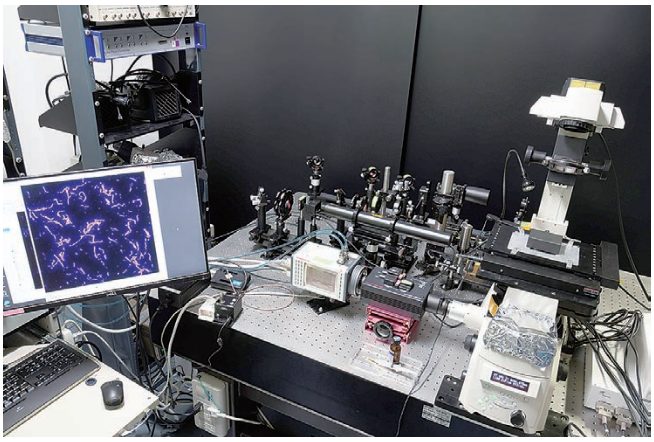


**Figure 3** **A total internal reflection fluorescence microscope is an optical microscope that enables visualization of fluorescence of single molecules. Near-field light emitted from the glass surface is used for illumination and to suppress background light.**

themselves. Obviously, such collective behavior is all programmed into the properties of the individual molecular machines. In contrast to human-made machines, this truly is bottom up control, with no commander.

Biomolecular motors perform most biological work with directed motion, such as muscles and dividing cells, and they work in the microscopic world of only tens of nanometers in size; only one thousandth of the thickness of a human hair. This world shakes vigorously, with some trillion collisions per second due to the motion of thermally agitated water molecules, so operation of these biomolecular motors is analogous to driving a car to your destination through a storm full of tornados.

Currently, it would be impossible to build a molecular machine from scratch that could operate under such conditions. There are technical difficulties, but even before that is the problem of establishing the most basic principles for what a reasonable design could be. In the way artificial macroscopic machines are usually designed, random thermal agitation is considered to be noise, and a large amount of energy is used to suppress it. On the scale of molecular machines, however, thermal agitation is much larger than the energy that can be expended per molecule so it cannot be ignored.

## Understanding design principles for creating new biological molecular machines

With research analyzing just existing biomolecular motors, which are a result of the unique history of life, it has not been easy to close in on the essence of unidirectional motion at the nanometer scale, even if we have been able to understand structure or function when applied to particular life processes. One effective way to clarify these principles, in addition to analyzing existing biomolecular motors, could be to take a constructive approach where desired functionality is achieved by combining various elements with simpler functionality.

According to the above-mentioned approach, we used the motor domain of a type of biomolecular motor called dynein as a motor core, and actin-binding domains for filament binding instead of the original microtubule-binding domain of dynein (Figure 1).

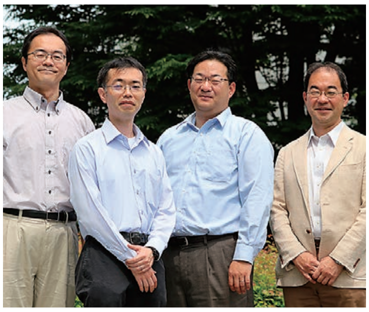
If, as has been conventionally thought, the interface with the rail had to be tightly coupled with the ATP hydrolysis activity*2 of the motor core, then introduction of a completely unrelated actin-binding domain would be expected to simply cause loss of motility. However, contrary to expectation, the new molecular motor was able to translocate an actin filament smoothly in one direction (Figure 2). We gathered detailed data on the correspondence between direction of motion and structure using a total internal reflection fluorescence microscope (Figure 3). We thus proposed the possibility that these biomolecular motors do not overcome the turbulence of thermal agitation, suppressing it by precisely matching the timing of enzymatic activity and filament binding/unbinding functions. Rather, they implement motion based on a simple mechanism that relies only on asymmetry in the structure of the interface to rectify the random motion of thermal agitation into one direction. This type of approach will rule out mysterious mechanisms that are found everywhere in biological sciences, and reveals the potential to access essential design principles for what materials are needed and how they are arranged in order for molecular machines to function.

## Future prospects

Research on designing new molecular machines with a desired function has just begun, but our research has already revealed a direction to some extent. In the future, we intend to create new artificial molecular machines based on those that give motility to living things, thereby explaining design principles, and creating highly-functional autonomous molecular machines that even surpass those derived from living things.

# A Silicon CMOS Wireless Receiver in the 300-GHz Band

## Toward ultra-high-speed wireless communications technology using the terahertz band



From the left: A. KASAMATSU, S. HARA, I. WATANABE, N. SEKINE

**Shinsuke HARA**
Senior Researcher
Frontier Research Laboratory
Advanced ICT Research Institute

After completing graduate school, Dr. HARA was Assistant Professor at Tokyo University of Science, Faculty of Industrial Science and Technology before joining NICT in 2013. Engaged in research on millimeter-wave and terahertz-wave CMOS circuits and nano-electronic devices. Ph. D. (Science).

**Issei WATANABE**
Senior Researcher
Frontier Research Laboratory
Advanced ICT Research Institute

**Norihiko SEKINE**
Research Manager
Frontier Research Laboratory
Advanced ICT Research Institute

**Akifumi KASAMATSU**
Executive Researcher / Associate Director of Frontier Research Laboratory
Advanced ICT Research Institute

**Research and development of terahertz wireless communication circuits in the 300-GHz band, which has not yet been allocated or used, using silicon CMOS technology was done in cooperation with Hiroshima University and Panasonic Corporation. A 300-GHz CMOS transceiver operating above the unity-power-gain frequency of CMOS was realized by developing several innovative circuit technologies, and a wireless link with the high data rates using multi-level modulation was demonstrated.**

### Introduction

Electromagnetic waves, including radio waves and light, are used broadly in industrial fields. Radio wave frequencies are allocated according to specific uses under the relevant regulations. Radio waves up to frequencies of 30 GHz are in general use, but with the proliferation of smartphones and other information terminals, radio resources are becoming depleted. The industry is also now entering a new phase of restructuring due to the evolution of the Internet of Things (IoT), Big Data, and AI, and wireless communication technology will increasingly play a major role. It will be essential to achieve wireless technologies capable of higher capacity and higher speed communication, and to do so, new radio resources must be exploited.

Millimeter- and terahertz (THz) waves are electromagnetic waves that occupy the range between radio and light, with wavelengths from 10 to 0.1 mm and frequencies from 30 GHz to 3 THz. They are not yet being utilized much and are an unexploited frequency band. Figure 1 shows the atmospheric attenuation characteristic in the low THz frequency range. The wide portion of the electromagnetic spectrum that can be transmitted with less distortion or absorption, which is called the "atmospheric window," occupies the frequency range from 182 to 325 GHz. The band above 275 GHz has not been allocated at all, and discussion regarding its utilization has begun in international standards organizations. If a wide band in this range could be secured and wireless communication implemented using multi-level modulation, which can transmit multiple values on one signal, high speed wireless communication over 100 Gbps would be possible. This would be more than ten times faster than speeds anticipated with fifth-generation (5G) mobile communication systems that will use the 28-GHz band. Realizing such ultra-high-speed wireless communication technology would make possible applications such as those shown in Figure 1.

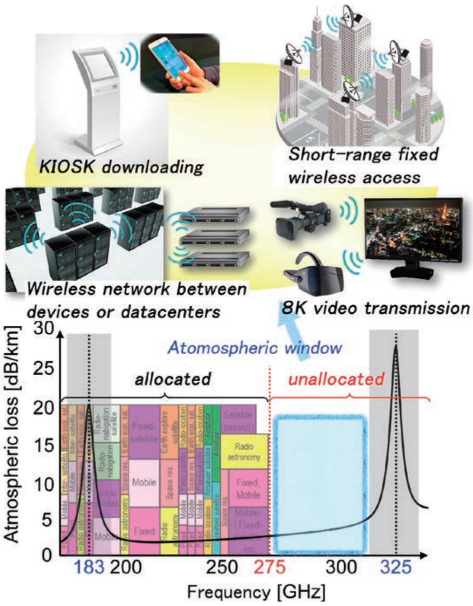
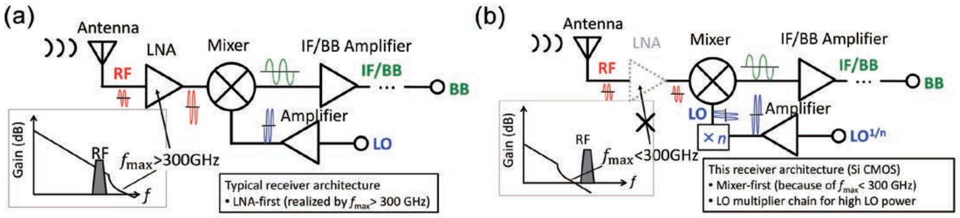
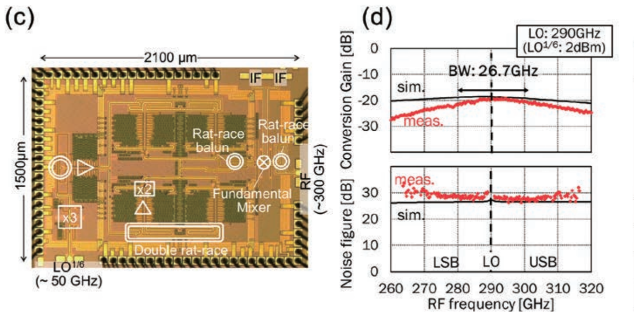



Figure 1 Atmospheric attenuation and frequency allocation in 300-GHz bands (below) and possible applications of terahertz wireless communication (above)

### 300-GHz silicon CMOS wireless transceiver

Silicon CMOS technology for constructing integrated circuits with millions or hundreds of millions of transistors is used in digital processing and memory circuits. To achieve broad use of ultra-high-speed wireless communication in the THz band, it would be desirable to also realize wireless communication circuits (i.e., transceivers) using silicon CMOS technology, so they can be integrated with digital processing and memory circuits. However, the unity-power-gain frequency ($f_{max}$), which is where the unilateral power gain rolls off to 1 (0 dB), is approximately 280 GHz for silicon CMOS transistors, which is not adequate for the wireless




(e)

| | 16QAM | 32QAM |
|---|---|---|
| Constellation | | |
| EVM | 12.2%rms | 8.8%rms |
| BER | 9.3 x $10^{-5}$ | 1.3 x $10^{-4}$ |
| Sym. rate | 8 Gbaud | 4 Gbaud |
| Data rate | 32 Gbps | 20 Gbps |

**Figure 2　Block diagram of (a) typical and (b) proposed wireless receiver, (c) chip micrograph of the 300-GHz CMOS receiver, (d) its performance characteristics, and (e) constellations from wireless communication tests**

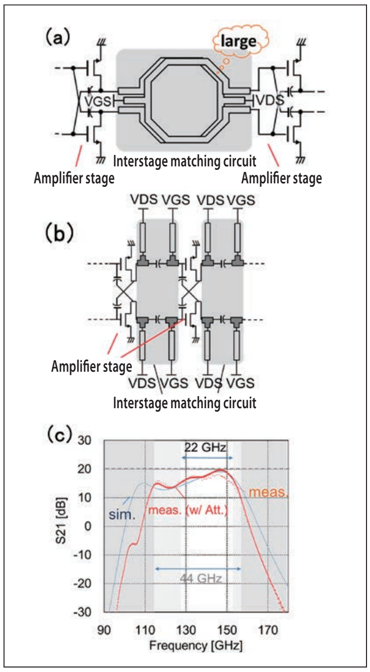



**Figure 3　Schematic diagram of (a) conventional and (b) proposed inter-stage matching circuit of differential amplifier, and (c) small signal characteristics of the proposed amplifier**

communication carrier frequencies of 300 GHz that we hope to achieve. Since only signals at frequencies below $f_{max}$ can be amplified, an amplifier for wireless communication in the 300-GHz band cannot be designed using silicon CMOS technology.

Recently, we presented 300-GHz silicon CMOS transceivers that resolve the above problem using several circuit technologies in collaboration with Hiroshima University and Panasonic Corporation. A wireless receiver which receives radio frequency (RF; 300-GHz band in this case) signals converts them to a lower frequency suitable for processing to recover the information. The received signals are weak and buried in noise, so normally an architecture with a low-noise amplifier to amplify the RF signal placed after the antenna is adopted. However, the 300-GHz band RF signal cannot be amplified using silicon CMOS transistors as explained above. Therefore, we adopted an architecture with a frequency converter (mixer) at the first stage. This mixer mixes the RF signal with a local oscillator (LO) signal of frequency upconverted to a frequency similar to the RF signal, converting to a signal of several GHz. To prevent the signal from being buried in noise, the noise figure must be reduced and the conversion gain of the initial mixer maximized, requiring a high LO signal power in the 300-GHz band. A frequency multiplier circuit able to generate a high-output LO signal was designed, which enabled implementation of a high-conversion-gain receiver. The receiver achieved a high wireless data rate of 32 Gbps in the 300-GHz band using a multi-level modulation scheme in wireless link evaluation with a silicon CMOS transmitter that was developed at the same time (Figure 2).

## Circuit elements for implementing a wireless transceiver

In our silicon CMOS transceiver circuits, 300-GHz band signals are generated by up-converting (multiplying) intermediate frequency (IF) signals at frequencies from 100 to 150 GHz at the last stage. To generate high power in the frequency converter or multiplier, a high-power, high-gain amplifier with wide bandwidth is needed in the IF band. The amplifier is composed of transistors, but the gain and bandwidth of a single transistor is limited, so a cascade connection of several amplifier stages is used to increase the bandwidth and gain. The impedance is different at the outputs and inputs between the cascaded connected stages, so inter-stage matching circuits are also needed to transfer the signal smoothly, without loss or reflection. However, such matching circuits occupy large area when implemented with conventional techniques, which seriously increases development and production costs. To resolve this problem, we developed a circuit layout technique to reduce the matching circuits to minimal dimensions. The technique enabled the size of differential amplifier to be reduced and implementation of high gain with wide bandwidth (Figure 3).

The silicon CMOS wireless transceiver which demonstrated the feasibility of THz high-speed wireless communication was implemented by adapting this technique as well as several newly developed techniques including a cubic or square mixer and power divider and combiner .

## Future prospects

In the future, we will improve the characteristics of our silicon CMOS wireless transceiver, continue development of related basic elemental technologies, and develop modules. In this way, we aim to soon realize ultra-high-speed wireless communications using 300-GHz band terahertz signals with silicon CMOS integrated circuits.

A part of this research was conducted as part of Ministry of Internal Affairs and Communications R&D to expand radio frequency resources entitled, "R&D on Terahertz Signal Device Basic Technology: 300-GHz band silicon semiconductor CMOS transceiver technology."

# Area Monitoring System —Search utilizing the local community—

Businesses are already being developed using GPS systems to look for elderly persons, children, or others needing monitoring, but there is potential for even more rapid, reliable monitoring utilizing IoT in traditional local communities. We introduce an area monitoring system based on a new idea, using new wireless systems that will be common in the future, and recruiting local collaborators as human resources.

## ■Technical overview and application field

Monitoring systems using GPS can find locations anywhere in the world, but they are not able to find locations indoors, where the GPS satellite signals do not reach. To overcome this problem, various indoor positioning systems have been developed, but indoor and outdoor systems are different so there is no single system to solve the problem. The service areas provided by the above-mentioned systems do not always agree with what is needed for monitoring and the monitoring accuracy.

For our monitoring scheme, participants from the area monitoring community are registered beforehand as search collaborators, along with their usual daily activities. Then, when search is needed for a person being monitored, these data are used to predict the behavior of each of the search collaborators. Search collaborators are further narrowed down based on their current location. Based on a real-time prediction of their activities, they are notified that they could encounter the person being monitored. Thus, selecting search collaborators according to the conditions and providing information about a possible encounter with the person being monitored reduces the burden on the collaborators and increases the probability of finding the missing person. If the missing person is found, family and other search collaborators are notified.

## ■ Quest for uses, applications, and collaboration partners

We envision using Wi-SUN, which is expected to expand throughout Japan soon, for positioning and communication in this monitoring system. If a beacon from Wi-SUN, which has a short range, is received, the location of the Wi-SUN device can be used as the location, whether indoor or outdoor. Thus, the rough location of the person being searched for is known, even without using a location from GPS or other system, and the device carried by those being monitored, which must run on batteries, can be compact and low power. NICT is planning demonstrations to verify the effectiveness of this technology. For further information, please contact our office at ippo@ml.nict.go.jp as shown below.

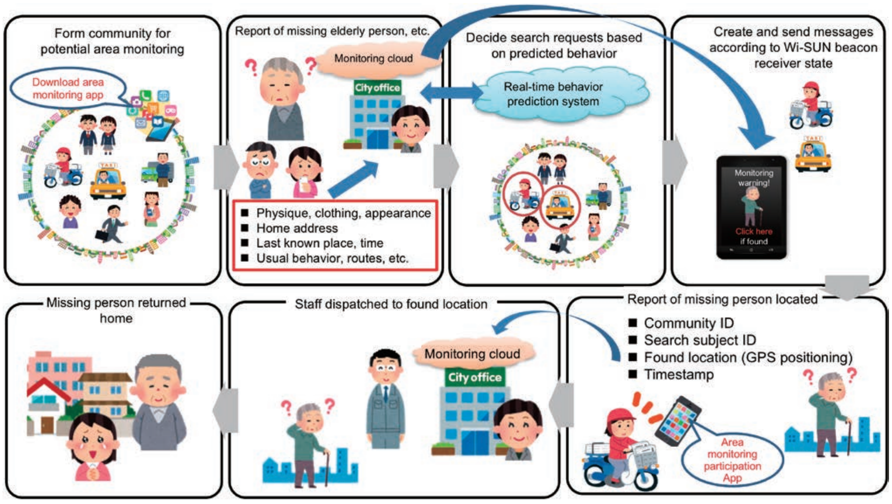



Figure Area monitoring system

**<Patent information>**

Publication No.: Patent Pub 2017-116980

Name of invention: Area monitoring system

**<Contact (Inquiries, etc.)>**

Intellectual Property Promotion Office, Innovation Promotion Department
E-mail: ippo@ml.nict.go.jp
TEL: +81-42-327-6950 FAX: +81-42-327-6659

# Awards

The Minister of Education, Culture, Sports, Science and Technology Prizes are given to persons who have achieved notable results in R&D or in advancing understanding in fields of science and technology. The Ichimura Prize is presented to technical researchers or groups conducting research at a university or a research institute that has contributed to advancement in a scientific field and has research achievements with practical applications.

## Minister of Education, Culture, Sports, Science and Technology
## FY2017 The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology

### Research Category, Prizes for Science and Technology

**Masahide SASAKI**
Distinguished Researcher, Advanced ICT Research Institute

**Mikio FUJIWARA**
Research Manager, Quantum ICT Advanced Development Center, Advanced ICT Research Institute

#### Comment from the Recipients

I am very honored to receive such a prestigious award. I am receiving it on behalf of the many others within and outside of NICT who were also involved in this R&D. I have been so fortunate to be able to conduct basic and applied research and development in such a world-class environment, supported and encouraged by successive management and my seniors at MIC and NICT, and working with such wonderful colleagues. I hope to continue working with these wonderful colleagues, bringing more dreams to reality.

#### data

- Date: April 11, 2017
- Description: Research demonstrating quantum information and communications and its applications

### Young Researcher Prize

**Taro YAMASHITA**
Senior Researcher, Frontier Research Laboratory, Advanced ICT Research Institute

#### Comment from the Recipient

I am very honored to be recognized for research results in superconducting single photon detectors (SSPD) at NICT. SSPDs are a technology that is already receiving attention in many fields such as quantum science, life sciences, and space applications. Further performance advances in the future are anticipated to expand the range of applications as well. I would like to thank my family, my laboratory colleagues, and other collaborating researchers for their constant support and will continue efforts to advance research on superconducting quantum devices.

#### data

- Date: April 11, 2017
- Description: Research advancing superconducting photon detectors and applications in quantum and life sciences

## The New Technology Development Foundation
## 49th The Ichimura Prize in Science for Distinguished Achievement

**Shinji NISHIMOTO**
Senior Researcher, Information and Neural Networks Laboratory
Center for Information and Neural Networks

#### Comment from the Recipient

I am honored to receive this award in recognition of our work to build a quantitative framework for analyzing human brain activity during complex natural audiovisual experiences, and for showing the potential for its applications in real society.

I would like to express deep gratitude to all who gave me direction and support in this work, both directly and indirectly. Encouraged by this recognition, I will continue to devote myself to advancing excellent research.

#### data

- Date: April 26, 2017
- Description: Development and application of brain modeling and decoding technology

Center: Shinji NISHIMOTO, Right: Mrs. NISHIMOTO

NICT NEWS No.465 AUG 2017
Published by
**Public Relations Department,**
**National Institute of Information and Communications Technology**
<NICT NEWS URL> http://www.nict.go.jp/en/data/nict-news/

4-2-1 Nukui-Kitamachi, Koganei, Tokyo
184-8795, Japan
TEL: +81-42-327-5392 FAX: +81-42-327-7587
E-mail: publicity@nict.go.jp
URL: http://www.nict.go.jp/en/
Twitter: @NICT_Publicity

**ISSN 2187-4050 (Online)**