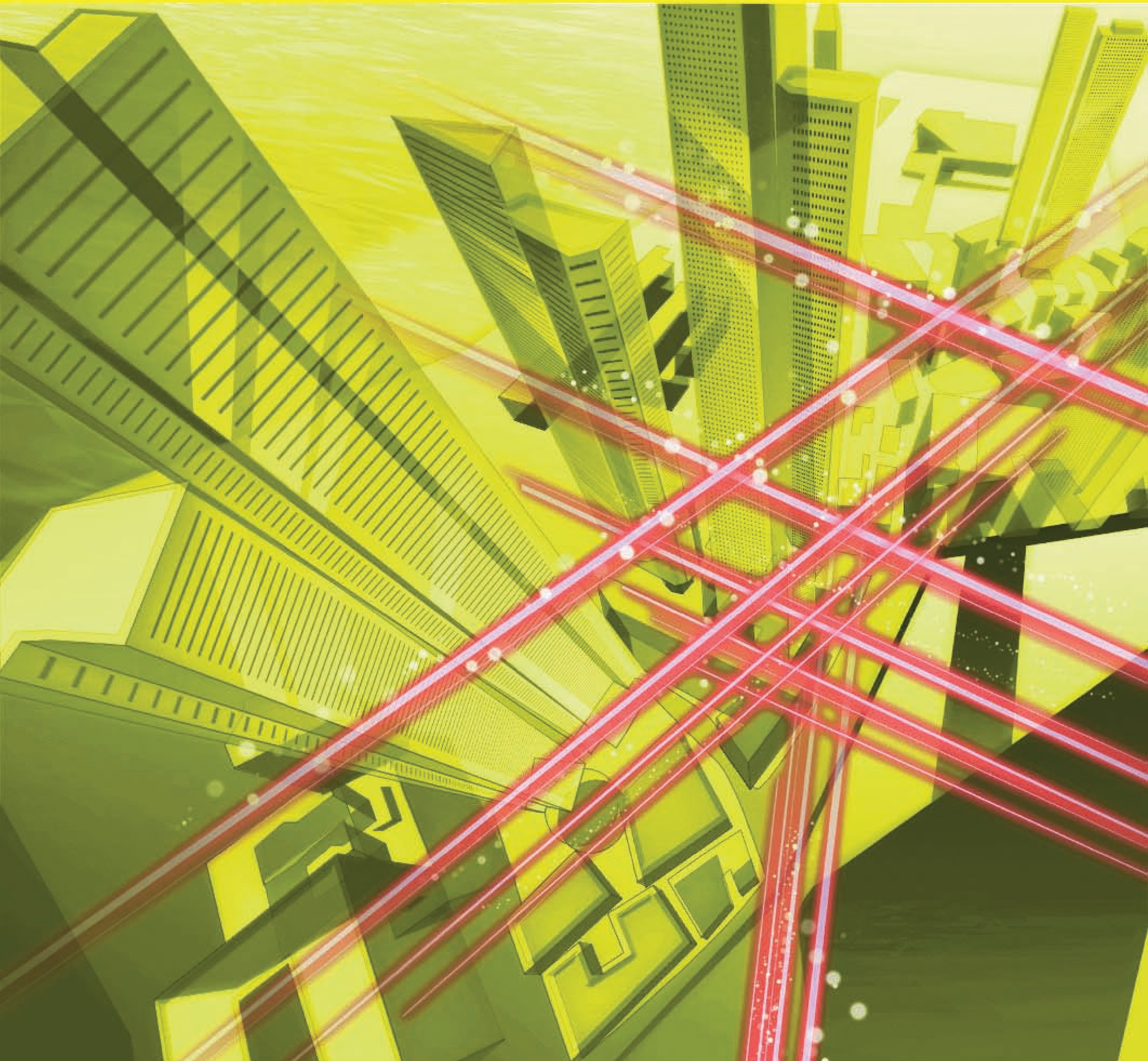
NTT Technical Review

9
2012



September 2012 Vol. 10 No. 9

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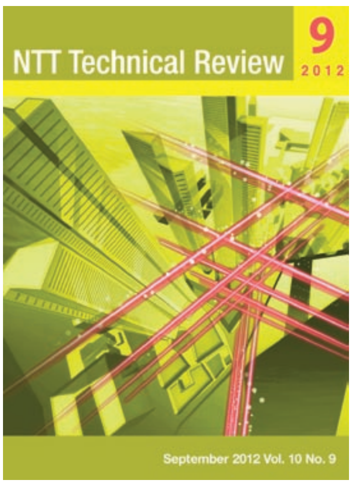


A Very Simple Strategy: Find Out Exactly What the Client Needs and How the Market Is Changing

Ettienne Reinecke
Chief Technology Officer
Dimension Data

Overview

Founded in 1983 in South Africa, Dimension Data is expanding worldwide as a comprehensive information technology (IT) solutions and services provider in the field of information and communications technology (ICT). Since joining forces with NTT in 2010, the company has been working to achieve an even higher level of performance. We sat down with Ettienne Reinecke, Chief Technology Officer, to learn about the growth strategy and future aspirations of Dimension Data in a volatile, changing market.

Seeking a very simple but highly effective strategy

—Mr. Reinecke, what has Dimension Data's strategy been up to now?

We have been moving forward by setting target markets while establishing very close communication channels with our clients. In this process, we have placed much importance on obtaining a thorough understanding of our clients' businesses and the problems they face and on developing our business accordingly.

The business environment has been undergoing major changes for more than ten years. The information and communications technology (ICT) industry has been maturing; clients have been seeking new business models; and macroeconomic movements, technical innovations, and business changes have been converging. These developments continue to impact the markets that we pursue and the strategies that we formulate. I believe that we too must change in line with these developments and that we must continue to evolve while keeping a watchful eye on key trends.

At the risk of repeating myself, our mission is to respond to our clients' needs. The efforts that we have made in creating maximum value have received high marks in client satisfaction measured by established research methods such as Gartner's Magic Quadrant.

—Your approach is to propose not what you want but what the client needs. How did you conceive of this approach?

It is a very simple but extremely effective strategy. Our clients—many of which are financial institutions—are involved in a wide range of business activities with diverse business models. However, all of them are deeply concerned about cost. They share a common desire to expand business in the current market using advanced ICT and to consciously control cost. Two key requirements to this end are a high level of technical competence and a reduction in investment costs. Accordingly, if we cannot fully grasp what the client needs and values, it will not be easy to provide a solution that matches the client's aspirations. For this reason, I believe that a sensational business can be developed if we can synchronize these key requirements with client goals.

What we want to provide are solutions that clients who want to move their businesses forward have never experienced. Our sincere desire to have our client experience such solutions underlies this way of thinking. Though very simple in essence, this idea has led to truly effective results and has, as a consequence, given birth to very amicable, long-term relationships with our clients.

Sincere, long-term relationships

—It appears that building long-term relationships is vital to Dimension Data for developing a robust, long-lasting business.

Let's look back at the business path that we have followed over the last 30 years or so. We started out as a very small-scale consulting company. At that time, even our clients realized that they were in the early days of applying information technology (IT) to expand business, but it was an era in which they would rack their brains trying to make sense of IT and figure out how best to use it. The history of our business therefore began with making proposals to clients who had a strong desire to use IT but did not understand how to use it to maximum effect. We then passed through various stages on our way to becoming a systems integrator. We began as a product integrator: in accordance with client needs, we proposed a set of appropriate products from diverse vendors. We then grew into a technology integrator: we gathered and analyzed a variety of new technologies and made proposals after assessing client needs. Now, as a systems integrator, our role is to understand and scrutinize ever-evolving ICT and provide our clients with optimal systems in a comprehensive manner. More recently, we have been presenting our clients with proposals that focus on service-oriented business models. All of our clients suffer from a severe lack of human resources and skills, as well as from strict demands placed on cost control. Needless to say, our clients and we too are being pressured in various ways by today's worldwide, macroeconomic conditions. Regardless, the secret to achieving a robust, long-lasting business even under difficult conditions such as these is to continue with our efforts in understanding each client's state of affairs and determining what services we should be providing.

—What kind of insights have you had through your relationships with clients?

As you know, we set sail on our quest to expand globally as a South African enterprise, and our first venture was in emerging markets, where efforts must begin with infrastructure building. I witnessed many struggles in trying to figure out how to go about building an infrastructure without adequate resources. But the times were changing with the coming of globalization, and we were determined to expand our business globally. But above and beyond our struggles, our clients found that they were entering an era in which they would be forced to globalize, and to support them in responding to that change, we ourselves had to change. That is, we had to find out what we should be doing to support our clients to overcome their IT challenges. While expanding our business in line with clients' needs, we continued to learn. We started out by asking ourselves: "What does *globalization* mean in the first place?" We then reflected on what lessons could be learned from our globalization efforts and what our outlook for the future should be. Of course, we made many mistakes (bad choices), but by constantly revising our approach and learning from these mistakes, we arrived at our present state. In the end, I feel that there's more to our business than just knowing about technology. It also means learning about actual business conditions and working on-site together with our clients in a truly participatory manner. In this way, we have been able to come up with many effective solutions. There are times when the market and industry find themselves at a crossroads, which is typically associated with some kind of groundbreaking event. I have seen how such a crossroads can stimulate innovation, and how the market and industry can undergo a sea change at such a time. In fact, I feel that we are entering a period of massive transformation right now. We can see this in cloud services: in the great changes that are taking place in the way cloud services are used and the volume of their use. We can also see it in the amazing advances that are taking place in mobile devices. A wave of great change is truly enveloping us all.

ICT is not the prime objective—it's a tool. In the end, the focus should be on people.

—As the market becomes borderless and development accelerates with such technological advances, how should we be making use of ICT?

Life today is forcing people to strive for a work-life balance to survive a rapidly changing environment while coping with stress from work and other areas of life. Under these conditions, it is not enough to focus on only our own environment—we must also keep abreast of how society and the world at large are changing. That is, we must figure out how to ride this wave of change. This is indeed a very tough challenge for all of us. On the other hand, this wave helps to promote technical innovation, so figuring out how to use new technologies to our benefit is one way of surviving a very stressful environment. A good example of this is learning how to make good use of the cloud, tablet computers, smartphones, and other modern devices that are now becoming an integral part of our lives. In short, it's not just about technology—it is also important that we apply our own knowledge or wisdom in coping with the situations that we face in our lives. Surviving this society is also very difficult for me, but I am making an effort to make good use of ICT to enrich my life. Whenever possible, I opt for a home-office work style that enables me to work and interact from home instead of having to go to the office. I am also concerned about managing my health and staying fit. For example, I've been making an effort during this stay in Japan to get into shape by running around the Imperial Palace whenever I can.

I think it would be great if everyone could live a life that achieves such a balance, but there is also something that I want everyone to remember. Technological advances have certainly made remote communication easier, but fundamentally speaking, communication between remotely located people is based on trust created through direct, face-to-face communication. I often say to my colleagues and fellow employees that communication is something that happens between people while ICT is a tool for facilitating that process. This may seem obvious, but misunderstandings in this regard can easily occur.

—Has this way of thinking penetrated the company?

We communicate using all kinds of technologies. Because we are expanding our business globally, we make use of ICT to establish contact with any of our offices anywhere in the world. I have set up such facilities in my home so that I can communicate with others in the company as needed. At the same time, I fully understand the importance of face-to-face meetings, and I hold such meetings at least once every quarter. Using ICT for work-related communications is a given, but I also encourage others to use ICT to develop close relationships with colleagues inside the company and even with friends outside the company unrelated to work. Enjoying outside interests and cultural activities can help one to appreciate others and cultivate even better human relationships. I believe that this approach to life is essential to good teamwork in the workplace.

—You talked about deepening one's understanding about cultural differences, but Dimension Data and NTT have major differences in corporate structure and culture. Out of the many ICT-related companies in the world, why did you think of tying up with NTT?

You might say that it's in our DNA as a South African company to give culture a high level of importance. As you can probably imagine, Africa is filled with a great variety of distinctive cultures. Perhaps it is because of this environment that South Africans are open-minded about multiculturalism—they respect cultural differences. During our negotiations with NTT, differences between our corporate cultures did not present an obstacle.

It took a little more than three years before a final decision was made, and during that time, we were able to develop an appreciation for each other's way of thinking and build a relationship. This, I believe, turned out very well. At that time, we had also received offers from other companies, but none of them wanted to take the time to carefully develop mutual understanding.

As you know, we are not a company that aims to create and provide something physical—what we do is provide services that our clients need. Accordingly, people who create services are the foundation of our business. And if these people—our staff—are not happy in their work, I think that it will be difficult to provide solid and compelling services. This idea is common to both Dimension Data and NTT, and this is why we joined forces.

—Looking forward, what do Dimension Data and NTT aspire to achieve through this tie-up?

Our relationship with NTT has so far given us access to R&D expertise and communication services that we previously did not have. I am convinced that we will be able to develop even stronger relationships with our clients against a background of NTT technologies as our role in this tie-up. Up to now, I have been focusing my efforts on three main areas: further expansion of cloud services, mobility, and playing a role in steering Dimension Data in the right direction. On looking at recent world trends, I feel that we, as an enlarged NTT Group, are well positioned to be successful in the changing business world. I believe that we can learn a lot from past experiences, and I would most certainly want to draw on these and do my best to understand the present—and provide some level of guidance for the future, within Dimension Data and the NTT Group.

Interviewee profile

■ Career highlights

Ettienne Reinecke received the BSc. degree in engineering from Stellenbosch University and the BSc. (Hons) and M.E. (Masters) degrees in engineering from the University of Pretoria, South African Republic. He joined Dimension Data in 1991 and was appointed Chief Technology Officer in 1998. He heads the Group's new technology and research areas and provides leadership for its solution and services strategies. He is also Dimension Data's executive responsible for joint development initiatives with the NTT Group. In 1996, he was Managing Director of Omnilink (a startup company and Dimension Data subsidiary), which the Group merged with Internet Solutions in 1999. In the late 1990s, he was closely involved with the Group's globalization efforts. From 1998 to 2002, he sat on the Board of Dimension Data Holdings before joining the Group's Executive Committee. In 2011, he helped establish Dimension Data's Cloud Business Unit. For several years, he has played the dual roles of Chief Technology Officer and Group Executive for Network Integration.

Exploring the Mechanism of Human Perception: A Challenge Befitting NTT

Shin'ya Nishida
Senior Distinguished Scientist
NTT Communication Science Laboratories

Shin'ya Nishida, an NTT Senior Distinguished Scientist, has used detailed psychophysical methods to clarify that human visual perception is achieved through the mutual interaction of processing modules in the brain and the integration of information about an object's movement, shape, color, and other attributes. We asked him about the implication of research, and, with the hope that he will continue to be involved in international activities, about his future objectives.

Explaining vision through psychophysics

—Dr. Nishida, please tell us about your main research theme.

I research the mechanism behind the way that people look at things. When you think about vision, what first comes to mind are words like eye and lens. The eye plays the role of a camera (input device) while neural circuits in the retina and brain do the processing. This scheme can extract useful information from images captured by the retina. The visual system extending from the eye to the brain consists of a component that plays the role of a camera and a component that acts much like a processor in a digital camera. Thus, in simple terms, my research aims to understand these two functions and the underlying mechanism, which I probe using psychophysical methods.

Psychophysics research has a long history. The question of how the human brain processes and interprets visual information captured by the retina has been examined by quantitatively analyzing judgments made by subjects on the basis of human perception.

The method of showing something to people and asking them how it looks has been used for about a hundred years. At one time, this was done using simple stimuli such as a picture drawn on a piece of paper. Recently, however, it has become possible to present images that had previously been difficult to prepare—such as artificial materials created with computer graphics—and to elicit responses about the material quality, such as "It appears shiny."

As a result of this research, it has gradually become clear that human visual perception is achieved through close coordination among cortical modules that process different kinds of information such as an object's movement, shape, and color.

—It seems that your research can be described as an attempt to determine and understand what people feel when they see something.

This might sound a bit vague, but you can call it research that investigates how we see an object itself and its shape, texture, movement, etc. (**Figs. 1** and **2**).

Let me compare human vision with machine vision. We would like machines to be capable of recognizing complex objects such as human faces. We human observers can immediately recognize our friends simply by observing their faces. However, trying to get a machine to recognize people in this way is difficult. Up to now, there has been no popular alternative to inconvenient methods such as passwords for identifying people.

For a human being, recognizing who you are currently talking to is an everyday occurrence, but asking a machine to do the same thing is far from easy. Moreover, when people look at something, they can sense it to be glittering, feel it to be beautiful, or judge it to have an interesting shape, for example. Needless to say, it is difficult to have a machine judge an object in the same way.

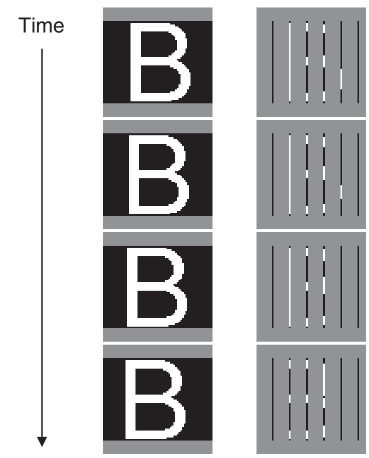
Thus, in a human being, there are a number of visual processing stages from sensing an input with the eye to having an emotional response to the input in the brain. If we don't understand the mechanism of, say, how we judge the quality and material of something that we are looking at, such as a metal or plastic object, we will not be able to understand how any subsequent emotion arises from them. Strictly speaking, we do not even know whether an emotional response is due to a conscious process of judging a characteristic like material or whether it is made through a separate, unconscious process. To fully understand the mechanism of human perception, we need to answer profound questions such as what is the role of conscious awareness.

—How would you go about explaining that function?

I would, for example, have a subject look at a motion picture and ask him or her to make judgments that would help me determine how human beings process motion-related information. That is, instead of measuring brain activity by some device, I would want to find out what the subject is seeing—I would listen to subjective information that only that person could access. Although devising what to present to a subject is, in a sense, a classic technique, we still make use of it in our cutting-edge research.

There has been much research recently on brain-machine interfaces, as in methods of estimating what is going on in the mind by capturing images of the brain through techniques such as magnetic resonance imaging (MRI). However, it is still at an elementary stage of research—rather than reading the mind, it has just begun to be possible to infer certain judgments in a piecemeal manner.

On the other hand, asking a subject directly, while a classic technique, provides a much richer



If the character "B" is viewed through fine slits, it is unreadable if it is stationary but readable if it is moving.

Fig. 1. Mutual interaction between movement and shape.

With highlights, the object seems to have a glossy appearance (upper image), but a simple manipulation of colors can eliminate the highlights and thereby decrease this sense of gloss (lower image).

Fig. 2. Example of texture research.

understanding of that person's state of mind. It is not easy to understand a person's mind state from only brain activity. Asking what a person senses and feels is currently the best way to access that person's state of mind or emotional state, and I don't believe that this will change in the future.

Up to now, it has been believed that different types of information such as that about movement, position, shape, and color have been processed separately within the brain. For example, it has been thought that information received about movement has not been used in recognizing the shape or color of that moving object. In accordance with this view, the brain region responsible for motion-related processing is different from the region responsible for processing shape or some other characteristic. However, I have uncovered a number of pieces of evidence for closely coordinated processing among these regions through mutually linked pathways, and I have shown that there are misunderstandings in the conventional view of this processing.

It all began by asking: "Why can human beings do things that machines cannot?"

—Dr. Nishida, how did you become involved in this research?

To begin with, I was a very argumentative student, and I thought that the act of seeing was somewhat mysterious. In high school, I was fascinated with the idea that the way in which something right in front of my eyes appeared to exist was simply the way in which my brain recognized it.

Planning for college, I thought that I would want to enter a field of study focusing on humans, and though initially unsure whether to pursue philosophy or psychology, I eventually entered the Faculty of Letters and majored in psychology. I also aspired to psychophysics with which I could objectively analyze somewhat vague and subjective areas such as mind and spirit by a scientific approach.

I found it interesting that cortical mechanisms could be clarified by simply analyzing what we perceive when looking at, for example, an optical illusion. Moreover, when I moved on to graduate school, I encountered a number of attractive research topics and somehow my path came to be set. I believe it all started with my desire to understand why human beings have capabilities that machines do not.

—In this research field, when do you feel that you have achieved something and obtained a good response?

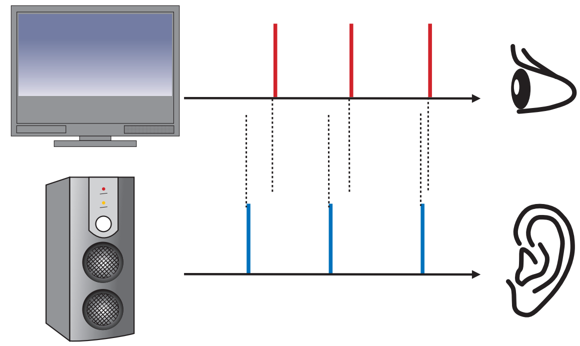
In research fields such as optical fibers and quantum computers, it should be easy to define results that are clearly recognizable and there should be many opportunities to receive concrete feedback. But in research targeting human beings, how to go about understanding the obtained results is a problem in itself, which makes it difficult to reach conclusions. But it is exactly for this reason that one can become addicted to such research and find it hard to extract oneself. It's like taking up the challenge of playing a difficult game that never ends. There is consequently still a question as to what standpoint this research should be conducted from, and I continue to reflect on this, though it makes me feel like a perpetual student.

However, science, being what it is, is a win-lose proposition—it's important to do good work, that is, compelling work, that can win the admiration of people. As I described earlier, research on material perception has expanded in recent years, and I believe that our results have contributed to this expansion. At the same time, I have been working in this field for many years with many questions still unanswered, and this can be depressing and it sometimes prompts me to question myself.

With regard to material perception, a pioneering paper that I submitted in 1998 helped me to recognize the value of my work, and from around 2000 on, my research began to draw attention from those around me. It was also reassuring to receive feedback indicating that my work had played a part in the growth of this research field.

I have also been recognized as a specialist in fields other than material perception such as visual motion and time perception, and I feel that I have been able to have an impact on those fields (**Fig. 3**). But as there are many things that are still not understood, I would like to make more original proposals in the future, and to this end, I plan to put my nose to the grindstone as a researcher with a worldview.

I worry every day about not obtaining convincing answers in my research, but this worry seems to dissipate when I hold discussions with young researchers in NTT. It is also fortunate that NTT does not demand short-term output. My aim is to exercise my ideas freely in order to come up with something novel that represents a leap from the present, and I can do this because I am not expected to set detailed targets.



If a lag between light and sound continues to be experienced, the subject will gradually stop feeling it. This illusion shows that the simultaneity of the visual and auditory senses is automatically adjusted.

Fig. 3. Example of research on judging time.

—What with obtaining no answers and forever seeking answers, your work is really an extraordinary endeavor. How do you keep motivated?

My research to date has not been very goal-oriented. Of course, there are various ideas about how my individually obtained results might be applied. My approach, however, is to feel my way along and break down barriers a little at a time in my quest for a breakthrough (imagine the videogame *Breakout*). What barrier to choose I leave to intuition. But once I began, I want to break it down completely even if it means doing it one piece at a time.

I am also conscious of dropping an idea that I have become overly attached to and looking at the problem from a different viewpoint. Nevertheless, it's not that I'm doing anything special to unleash new ideas. Call me obstinate or non-conformist, but this is just the way that I enjoy thinking.

I could not have reached where I am today without the many things that I learned from overseas pioneering researchers in their journal papers. I have recently had opportunities to talk with some of them at academic conferences, and they really enjoyed hearing this. Perhaps they felt that I was continuing in their footsteps and carrying on their ideas. They made comments about their expectations of me and about our common approaches, which I was very glad to hear.

Being a little different from others is fine. Take joy in different ways of thinking!

—What advice would you give to young researchers?

Each and every researcher holds a completely different worldview, so there will always be some misunderstandings between them. Still, enjoying such differences can be a meaningful thing.

Although it is a characteristic of Japanese to try to reach mutual understanding with others, I believe that researchers are different—they are naturally argumentative. In research, it's important to disagree. I would like young researchers to enjoy the fact that people can have different viewpoints and ways of thinking.

I also believe that it is not good to overly study other people's work or listen excessively to what other people say. You will become blind to your differences from other people unless you can listen while having your own hypotheses and way of thinking. Isn't it true that each person is born with something special? That, I feel, is the key to understanding researchers. Of course, there are some occupations that call for an ability to gather up and disseminate information correctly, but in the case of researchers, I think that they must first be able to develop a different perspective from other people instead of trying to achieve a balance with those around them. There's no need to be a good boy or good girl. I never thought that being different from other people was a bad thing; indeed, I purposely set out to be a little different.

Researchers are often asked to write about and explain their research in an easy-to-understand manner. However, for researchers who have unique perspectives on things, explaining their findings in a way that anyone can understand on the basis of common sense or accepted wisdom would appear to be difficult. In today's society, though, that excuse is becoming more difficult to fall back on. The situation is such that people without good social and communication skills may fail to win approval or praise. Perhaps researchers will now be asked to have good writing skills and the social awareness of screenwriters and movie directors! I truly feel that this is necessary for people who specialize in certain fields like myself in brain science. I would therefore like young researchers to cultivate a sense of balance so that their writings will attract the interest of the general reader while still being grounded firmly in science.

—Dr. Nishida, what objectives have you set for yourself looking forward?

I am still looking for answers, so it would be great if I could put myself again in a situation in which I could devote myself to round-the-clock research. I want to go forward, but not in any particular direction. I want to open up new areas that have yet to be fully explored, and I want to expand my endeavors freely without being confined to a particular format. I believe that new things are born when one engages and clashes with new people. I want to continuously challenge myself by examining my current situation and asking myself whether that's good enough.

Shin'ya Nishida

Senior Distinguished Scientist, Sensory Representation Research Group, Human Information Science Laboratory, NTT Communication Science Laboratories.

He received the B.S., M.S., and Ph.D. degrees in psychology from Kyoto University in 1985, 1987, and 1996, respectively. After a two-year stay at ATR Auditory and Visual Perception Laboratories in Kyoto as a research associate, he joined NTT Basic Research Laboratories in Tokyo (now Communication Science Laboratories) in 1992. He is a member of the Vision Society of Japan, the Japanese Psychological Association, the Japanese Psychonomic Society, and of Vision Sciences Society. He serves as an editorial board member of the *Journal of Vision* and the *Vision Research*, as a visiting professor at the Center for Multidisciplinary Brain Research, National Institute for Physiological Sciences, and as a member (RENKEI KAIIN) of the Science Council of Japan. He received the Second JSPS (Japan Society for the Promotion of Science) prize and the JPA (Japanese Psychological Association) International Prize in 2006.

Research Frontier of Quantum Computers

Hiroshi Yamaguchi

Abstract

This article introduces quantum computing, the topic of the Feature Articles in this issue. More than ten years have already passed since the study of devices for quantum computers began. During this time, the technology for manipulating the quantum state of the basic element, the qubit, has greatly improved, but fundamental problems have also been revealed. The Feature Articles in this issue review new attempts underway in our laboratories to overcome such problems.

1. Development and application of quantum physics

The quantum computer has been attracting attention because of its potential ability to perform extremely high-speed signal processing. More than ten years have passed since the start of competitive studies of hardware for quantum computing. The basic element for configuring a quantum computer is called a quantum bit, or qubit. Research toward achieving an ideal qubit has been actively pursued using systems having various physical units.

The quantum computer operates according to the principles of quantum mechanics, a fundamental theory of physics. Quantum mechanics describes behavior in the natural world very differently from Newton's classical mechanics, although classical mechanics is the source of our common sense. For example, the statements "mechanical systems all have the aspects of both waves and particles" and "dynamical systems can all be present at the same time in multiple locations" arise as a consequence of quantum mechanics. These ideas indicate that a physical system has inherent multiplicity, referred to as quantum superposition, and this multiplicity of physical systems is the key mechanism for massively parallel computation in a quantum computer.

Accepting these ideas also raises questions of a philosophical nature: Are our bodies also like waves and can they exist simultaneously in two places? How about the human mind? Can it also exist in two places at the same time? And if so, then if it dies in one place, does it also die in the other place? Since the basic theoretical framework of quantum mechanics was established nearly a century ago in the 1920s, there have been ongoing discussions about questions such as these. After serious debate over the course of many years, physicists have come to believe that the theory is infallible. To date, they have found that all experimental observations are successfully explained by quantum mechanics.

From the viewpoint of engineering applications of quantum mechanical phenomena, quantum mechanics has led to the creation of innovative technologies such as semiconductor devices and lasers. For instance, the band structure in a semiconductor could not exist without quantum-mechanical effects, and lasers would not work without quantum mechanical interaction between light and matter. However, technology that uses an essential aspect of quantum mechanics, such as the idea that an electron can exist in two places at the same time, has been explored only very recently in the form of quantum information technology, such as quantum computers and quantum cryptography.

We have been studying microfabrication and nanofabrication technologies for the development of electrical and optical semiconductor devices. As a new application, the research of semiconductor and superconductor devices, where the quantum mechanical nature appears, was initiated more than ten years ago (**Fig. 1**). Now, it is even becoming possible to control the quantum mechanical multiplicity in these structures. Major technological advances using the essence

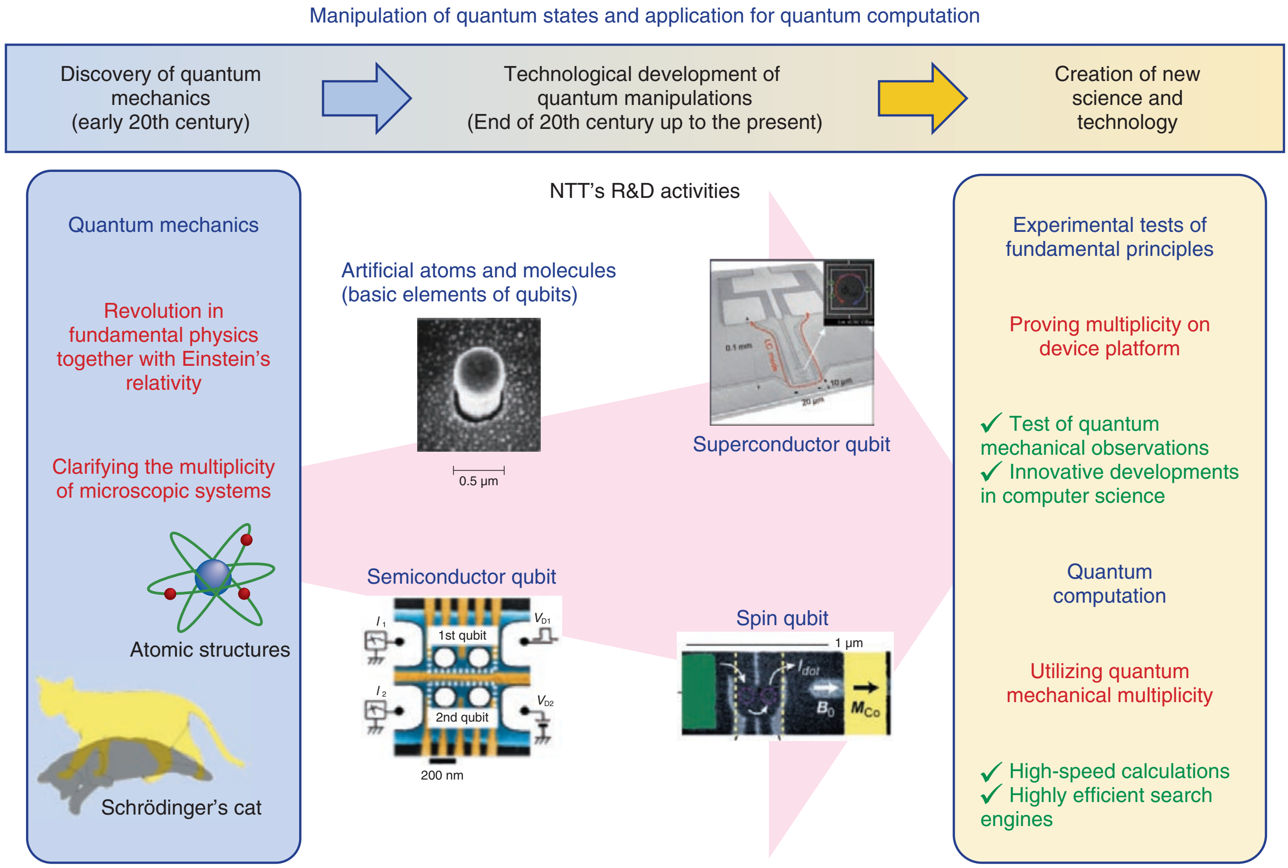


Fig. 1. From the discovery of quantum mechanics to its application.

of quantum mechanics promise ultrafast and highly energy efficient database searches and calculations. They can be used in applications such as the discovery and design of new materials and pharmaceuticals.

2. Challenges of quantum computer research

As a result of various attempts over the past ten years, a technique for precisely controlling the superposition of qubit states "0" and "1" has progressed significantly in individual studies. Simultaneously, serious problems have been encountered as we proceed toward the development of more realistic quantum computers. One of the biggest problems is that it is not easy to extend the present scheme to multibit systems. For a *classical* computer, once you have completed the development of one element (such as an OR gate or AND gate), joining elements to construct a multibit system is not difficult. The basic elements linked by wiring perform the combination of their operations and there is no essential problem in multibit operation. On the other hand, qubits face an essential problem concerning multibit operations. That is, the quantum superposition cannot be maintained for a long enough time to perform multibit operation. There is a limit to the amount of time for *coherent* operation. With the current level of technology, it is not too difficult to manipulate the quantum state once, but when we try to run it multiple times, the quantum state is easily broken and the operation cannot continue.

This problem had been regarded as important from an early stage and research has been seeking to find a qubit that maintains the quantum superposition state for a longer time. Various different physical systems of qubits have been devised and each has been found to have both advantages and disadvantages. One system allows very fast computation but the quantum state immediately becomes corrupted; another is not good at bit operation but the quantum state can be maintained for a long time. Moreover, some systems are well suited to the combination of multiqubit gates, while others are not, although they have excellent performance in single-qubit operation. Therefore, constructing a hybrid system consisting of different types of physical systems with different advantages is regarded as the right direction, rather than proceeding to force the construction of the best system with qubits of only a single type.

The Feature Articles in this issue introduce NTT's recent research related to a variety of different types of qubits. These studies are at different stages of research, ranging from confirming operation as a qubit to just exploring basic physical properties. Below, I briefly describe the characteristics of each quantum system.

3. Various physical systems studied for configuring hybrid qubit systems

3.1 Superconducting circuits

Superconductivity is a phenomenon in which the electrical resistance of materials vanishes at low temperature. Current flowing through a circuit loop made of superconductors never stops because the material has zero resistance. This current is very stable, and we are attempting to use it to represent a quantum state. The superconducting qubit is one of the most successful and advanced systems among solid-state quantum devices.

The basic structure of the superconducting qubit is shown in **Fig. 2**. The parts for *disturbing* the superconducting current flow, called Josephson junctions, are formed on a looped circuit consisting of superconducting aluminium. These junctions mix the currents flowing clockwise and anticlockwise to achieve a quantum superposition state, where the current simultaneously circulates in two opposite directions. The superconducting circuit offers very good quantum superposition control, but trying to configure multibit operations only with superconducting qubits has been a major challenge. Instead, we have recently been attempting to integrate the circuit with *quantum memory* implemented in other quantum systems. More specifically, we are working to study the quantum spin states used as the memory with defect complexes called NV^- centers in diamond. In addition, a major issue is how to read out the qubit state without destroying it because the signal induced by the current is very weak. This set of Feature Articles introduces studies addressing these two challenges.

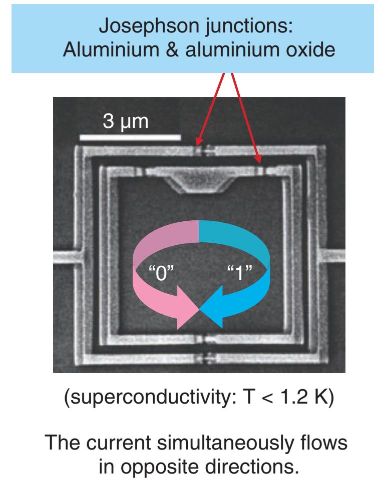


Fig. 2. Superconducting qubit.

3.2 Electron spin

Spin is a quantum mechanical property of elementary particles such as electrons and protons (**Fig. 3**). It is a kind of angular momentum that the particle possesses in itself, so spin is often regarded as rotation about an axis. Quantum theory combined with Einstein's theory of relativity requires an electron to eternally exhibit angular momentum, i.e., the rotation is sustained forever. This is similar to a superconducting current and can represent a quantum state depending on whether the clockwise or anti-clockwise direction of rotation is sustained.

Electron spin is used in several applications, the most well-known of which is magnets. The properties of a magnet could not be generated without electron spins. We can intuitively understand this by considering electron rotation to induce a kind of rotating current that generates a magnetic field like a coil or solenoid.

The possibility of obtaining long-lived quantum states for spin qubits has been pointed out. For example, the spin state in an NV^- center in diamond is reported to be maintained for a time on the order of milliseconds. This is longer by two or three orders of magnitude than that in solid-state qubit systems, so its use for quantum memory is highly promising. An article in this issue describes a study on controlling electron spins by applying a voltage to semiconductor devices and one that covers quantum memory using NV^- centers.

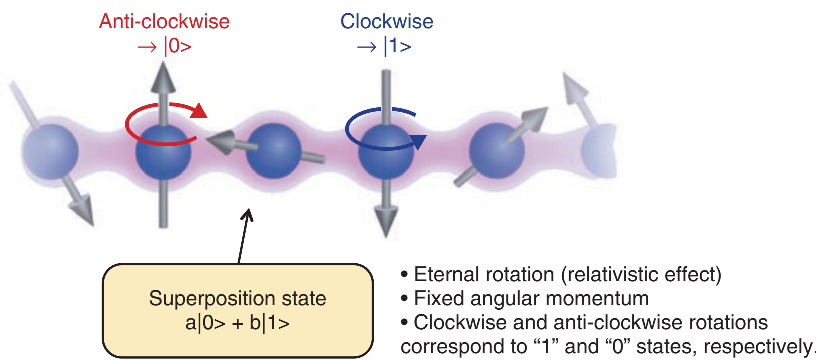


Fig. 3. Schematic explanation of electron spin.

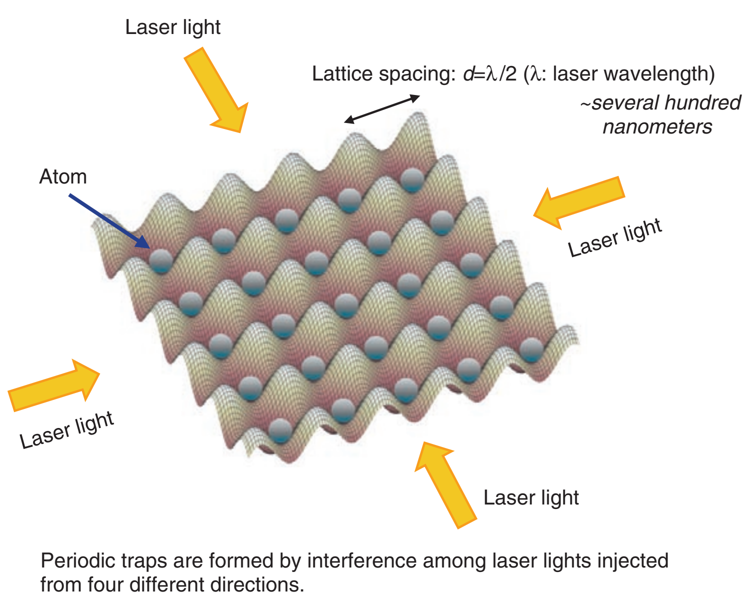


Fig. 4 Schematic illustration of optical lattice.

3.3 Cold atoms

Until recently, cold atoms had been considered to be unsuitable for developing solid-state quantum computers because they are not available in solid form, although they can sustain quantum states for a very long time. However, in recent years, they have become strong candidates for solid-state qubits following successes in integrating cooled atoms on a piece of solid material, called an atom chip.

The atom is one of the physical systems where quantum phenomena were confirmed at a very early stage in the history of quantum mechanics. This is because atoms in gas are isolated from each other, which can maintain the quantum mechanical nature. However, if you try to control the quantum state, the atoms move too rapidly to detect and control the individual quantum states.

The solution to this problem is to cool the atoms. The rapid motion is caused by thermal energy, so lowering the temperature can confine the atoms in a limited space. In practice, it is not easy to cool atoms down to temperatures where atomic motion is sufficiently suppressed, but a technique called laser cooling is promising for this purpose. This issue introduces a method for applying laser cooling in an attempt to construct a regular lattice of cooled atoms (**Fig. 4**).

4. Diversity and future of quantum technologies

Einstein's famous theory of general relativity, proposed in 1915, provided many extraordinary predictions, such as that time passes at different speeds on the ground and in space, and it completely changed our world view. Although the theory has had a great impact on the scientific community, people believed until recently that it would not be of practical use in technologies relevant to our daily life because its influence is extremely small. However, the global positioning system (GPS) that we currently use would be inaccurate if its design did not take into account the theory of general relativity. Advances in technology are surprisingly fast, and technologies that were initially thought to be impossible spread very quickly once they have been developed.

As mentioned already, nearly a century has already passed since the discovery of quantum mechanics but the study of how to use its essence in practical technology has begun only very recently. In that sense, the study of the quantum computer is still just beginning and it will certainly take a long time to come to fruition. Research scientists love to try to achieve major breakthroughs, and the research activities presented in the Feature Articles in this issue are examples of such attempts. By combining the techniques covered here, we may be able to create quantum computers with excellent performance in the near future. Alternatively, some researchers expect big developments in applications of quantum phenomena completely different from the quantum computer. Quantum mechanics is very different from classical mechanics, which governs the basic principles of current technology, and it has such a wide diversity that the quantum computer may well be only one example of its applications.

Hiroshi Yamaguchi
Senior Distinguished Researcher and Group Leader of the Nanostructure Technology Research Group, NTT Basic Research Laboratories.

He received the B.E. and M.S. degrees in physics and the Ph.D. degree in engineering from Osaka University in 1984, 1986, and 1993, respectively. He joined NTT Basic Research Laboratories in 1986. His current interests are micro/nanomechanical devices using semiconductor heterostructures. He has been a guest professor at Tohoku University since 2006. He is a fellow of the Institute of Physics and a member of the Japan Society of Applied Physics, the Physical Society of Japan, and IEEE.

Coherent Coupling between a Superconducting Qubit and a Spin Ensemble

Shiro Saito, Xiaobo Zhu, William John Munro, and Kouichi Semba

Abstract

This article reviews an experiment that demonstrated the principle of quantum memory operation in a superconductor-diamond hybrid system. Superconducting qubits have excellent controllability and scalability but short memory (coherence) time because they are artificial structures; on the other hand, electron spins in diamond are natural structures and have the opposite characteristics: they show extremely long memory times (seconds or greater) but are hard to control and manipulate. A superconductor-diamond hybrid system could offer the best properties of these systems without the associated disadvantages.

1. Introduction

The coherent control of quantum two-level systems, which are applicable to quantum bits (qubits), has attracted significant interest in the context of quantum computing and quantum information processing. Among the various candidates for quantum bits, superconducting qubits based on Josephson junctions have gained in importance because of their controllability and scalability. Their coherence time has reached a few tens of microseconds [1], compared with several nanoseconds at first in 1999 [2]. A few qubit gates have been demonstrated in superconducting circuits [3]. To execute larger and more useful quantum algorithms in the future though, it will be necessary to achieve a long coherence time. However, we are unsure whether this can be achieved solely with superconducting circuits.

The key components of a conventional computer are the central processing unit (CPU) and the random access memory (RAM) (**Fig. 1**). Each component plays its own unique role. The CPU processes the information while the RAM stores it. On the other hand, superconducting qubits have played the roles of both a processor and memory. In view of the above-mentioned issues, NTT has aimed to create a hybrid of superconducting qubits and another suitable system that can store quantum information for longer times [4] (**Fig. 2**).

2. NV^- centers in diamond

Nitrogen-vacancy (NV^-) centers in diamond have attracted significant attention as a potential candidate for a quantum memory for superconducting qubits. The NV^- center is a complex defect in a diamond crystal, formed of (1) a nitrogen (N) atom substituting for a carbon atom and (2) an adjacent vacancy (V) (**Fig. 3(a)**). As shown in **Fig. 3(b)**, its electron state is spin 1 with a zero field splitting of 2.88 GHz between the $m_s = 0$ and ms = ±1 states at zero magnetic field, where ms is the magnetic quantum number. The electron spin is known for its long room-temperature coherence time of 2 ms [5], so it seems to be suitable for a quantum memory. We can perform a memory operation under low magnetic fields because the zero field splitting of 2.88 GHz is compatible with the transition frequency of superconducting qubits. Furthermore, there is an optical transition in addition to the microwave one, so we may be able to create a

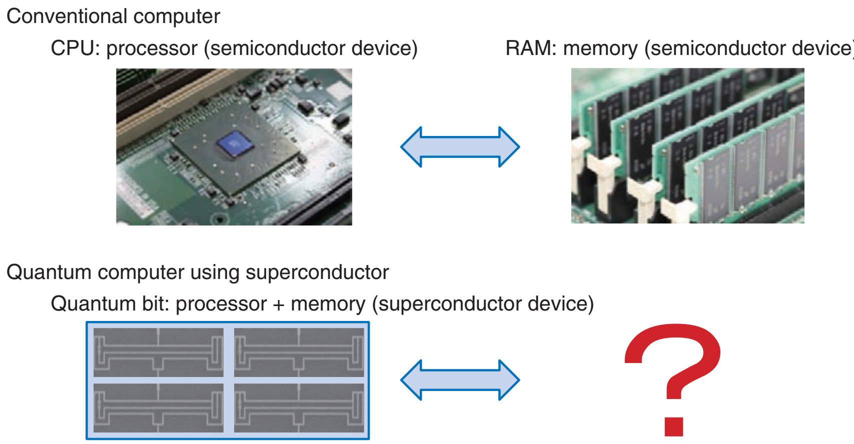


Fig. 1. Components of a computer.

	Controllability, scalability	Memory time (coherence time)
Superconducting qubits	Good (various circuit designs)	Poor (coupling to noise environment)
NV⁻ centers in diamond	Poor (weak coupling between spins)	Good (isolated from external noise)

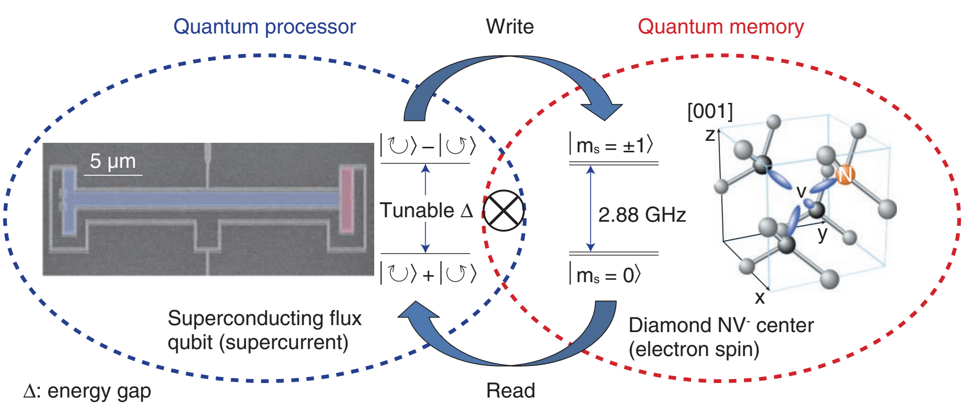


Fig. 2. Superconductor-diamond hybrid system.

quantum transducer—a microwave-to-optical frequency converter. This would be a key technology for quantum repeaters, quantum networks, and quantum computers.

3. Gap-tunable superconducting flux qubit

A superconducting flux qubit consists of a superconducting aluminium loop with three Josephson junctions. One of them is $\alpha \sim 0.8$ times smaller than the other two, which makes its Josephson energy proportionally smaller, i.e., equal to $\alpha \times E_J$ (see **Fig. 4(a)**). The system works as a quantum two-level system, that is, a qubit, when we apply an external magnetic field $\Phi_{ex} \sim (m+1/2)\ \Phi_0$ through the qubit loop (here, m is an integer and Φ_0 is the magnetic flux quantum). Figure 4(a) shows the lowest two energy levels of the system when $\Phi_{ex} \sim 1.5\ \Phi_0$. The clockwise circulating current state |R> and the anticlockwise one |L> are the energy eigenstates when Φ_{ex} is far away from 1.5 Φ_0. These states are composed of persistent currents $I_p \sim 300$ nA. The equal superposition states between |L> and |R> are realized at the degeneracy point where $\Phi_{ex} = 1.5\ \Phi_0$ because of tunneling due to the

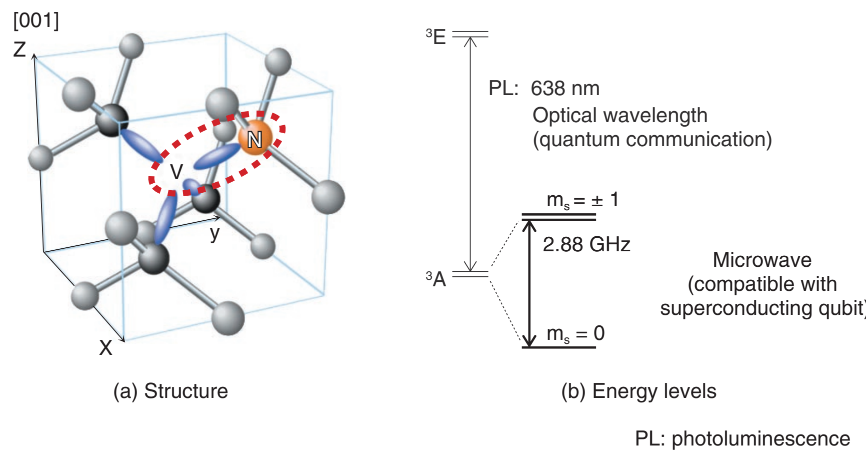


Fig. 3. NV- center in diamond.

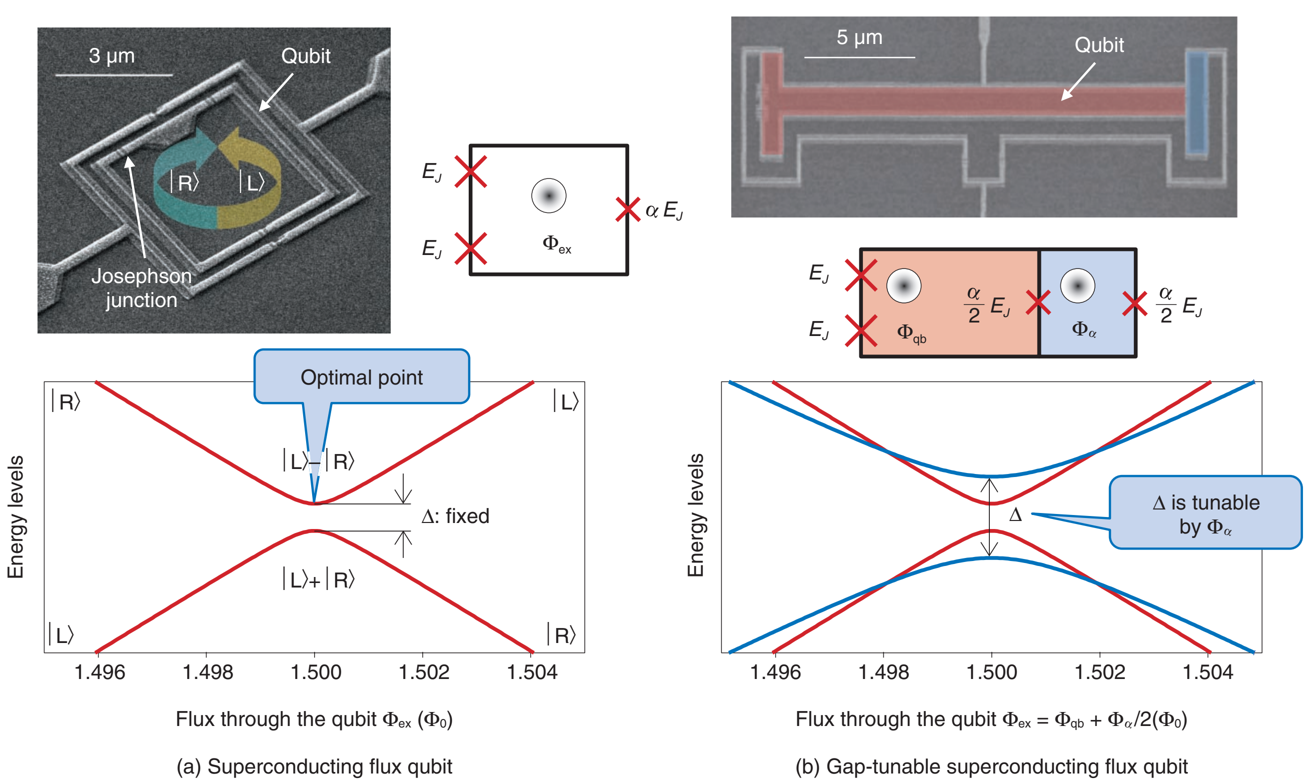


Fig. 4. Superconducting flux qubits and their energy levels.

charging energy of the junctions. The tunneling causes energy anticrossing between |L> and |R>, so the transition energy between the ground state and the excited state of the qubit is a minimum at this degeneracy point, which is called the *optimal point* because it is where the qubit is immune to external flux noise and exhibits its longest coherence time.

We can control the energy gap Δ of the standard flux qubit at this optimal point by an appropriate design of the junction area ratio α; however, we

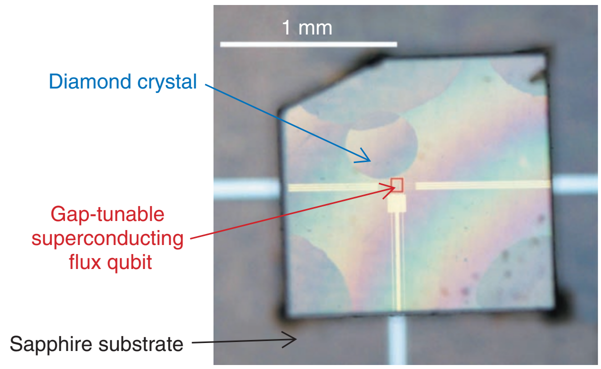


Fig. 5. Superconductor-diamond hybrid system.

cannot change it after sample fabrication. For our purposes, we need a gap-tunable superconducting flux qubit (**Fig. 4(b)**) in order to tune our qubit in resonance with other quantum systems, for example, an NV^- spin ensemble, while keeping it at the optimal point. We therefore need to replace the smallest junction (α junction) by a dc-superconducting quantum interference device (SQUID), whose E_J can be controlled by the external flux through it. The energy gap Δ can then be tuned in-situ by several gigahertz within a few nanoseconds [6]. The fact that a typical gap is between 1 GHz and 10 GHz thus indicates excellent compatibility with an NV^- spin ensemble in diamond.

4. Superconductor-diamond hybrid quantum system

The coupling strength between two physical systems is the key factor necessary for quantum memory operation in hybrid systems because the time taken to transfer information between the systems is inversely proportional to the coupling strength, so faster operation within its coherence time leads to high-fidelity operation. In the case of the coupling between a flux qubit and the NV^- spin ensemble, reducing the spatial distance between them increases the coupling strength because the spin ensemble couples to the qubit through the magnetic field induced by the qubit's persistent current I_p. Moreover, increasing the density of the NV^- spin leads to a stronger coupling because the coupling is enhanced by a factor $\sqrt{N}$ owing to a collective effect when the qubit couples to N electron spins. Therefore, it is important to prepare a diamond crystal that contains a high density of NV^- centers.

To achieve this, we injected carbon ions into a high-pressure high-temperature (HPHT) synthesized diamond crystal and annealed it in vacuum. We estimated the density of NV^- centers to be N ~ 1.1×10^{18} cm^{-3} by comparing the photoluminescence spectroscopy from a single center with that of our ensemble.

We fabricated our superconducting flux qubit on a sapphire substrate by using electron beam lithography and a shadow evaporation technique. The diamond crystal was then glued on top of it, achieving a spatial separation of less than 1 μm. The hybrid sample after mounting of the diamond crystal is shown in **Fig. 5**. We estimated the coupling g_i between a single NV^- spin and the flux qubit to be approximately 8.8 kHz from the geometrical configuration. This gave the estimated collective coupling $g_{ens(estimated)}$ as about 50 MHz for the NV^- center density.

5. Spectroscopy

We performed microwave spectroscopy measurements at 12 mK using a dilution refrigerator. The spectrum of the flux qubit with the diamond crystal shows a clear energy anticrossing at 2.88 GHz (**Fig. 6(a)**) corresponding to the transition frequency of NV^- spins. On the other hand, the spectrum taken before the diamond was mounted (**Fig. 6(b)**) does not show an anticrossing. From the above results, we can conclude that the splitting at 2.88 GHz comes from the strong coupling g_{ens} between the flux qubit and the spin ensemble. The coupling g_{ens} of 70 MHz is in good agreement with the coupling $g_{ens(estimated)}$ estimated using the NV^- center density.

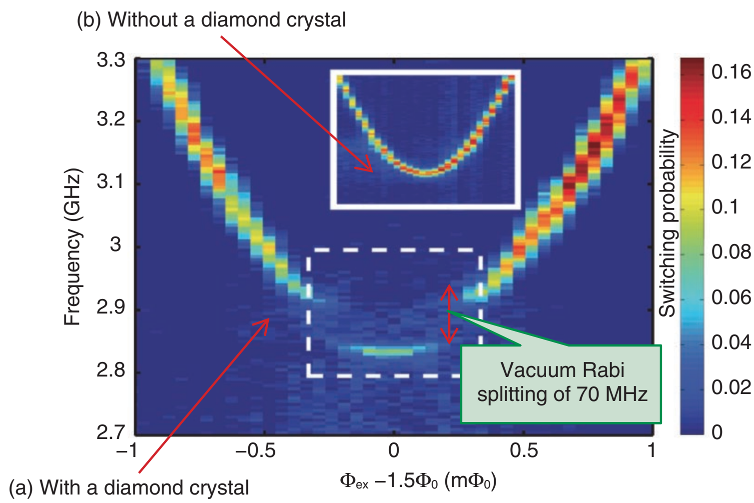


Fig. 6. Spectra of a superconducting flux qubit.

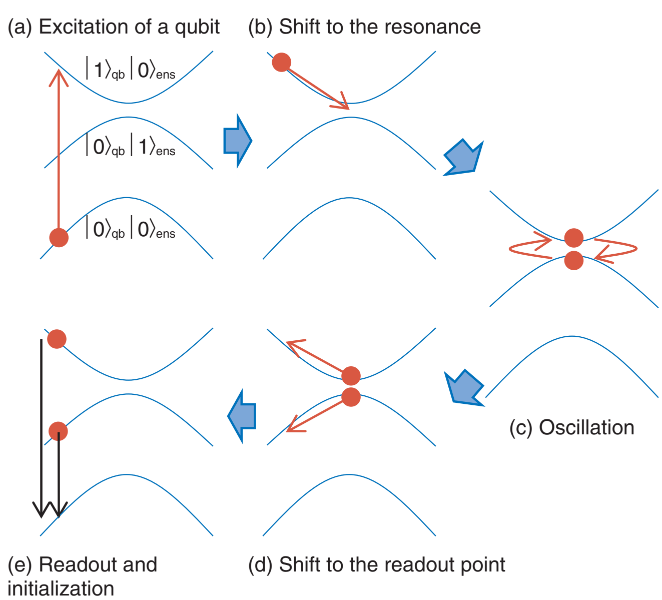


Fig. 7. Measurement sequence for observing vacuum Rabi oscillation.

6. Time domain measurement

We performed time domain measurements according to the sequence depicted in **Fig. 7** to demonstrate memory operations, that is writing to the spin ensemble and reading from it. First, we excited only the flux qubit by applying a microwave π-pulse to it when the qubit and the spin ensemble were well detuned (Fig. 7(a)). The qubit was quickly tuned by Φ_{ex} into resonance with the spin ensemble (Fig. 7(b)). This tuning (much faster than the coupling strength g_{ens}) causes a non-adiabatic transition, and the flux qubit can then start coherently exchanging a single quantum of energy with the spin ensemble as follows (Fig. 7(c)):
$|1\rangle_{qb}|0\rangle_{ens} \Leftrightarrow |0\rangle_{qb}|1\rangle_{ens}$,
where qb and ens indicate the flux qubit and the spin ensemble, respectively. The 0 (1) represents the ground (excited) state of each part of the hybrid

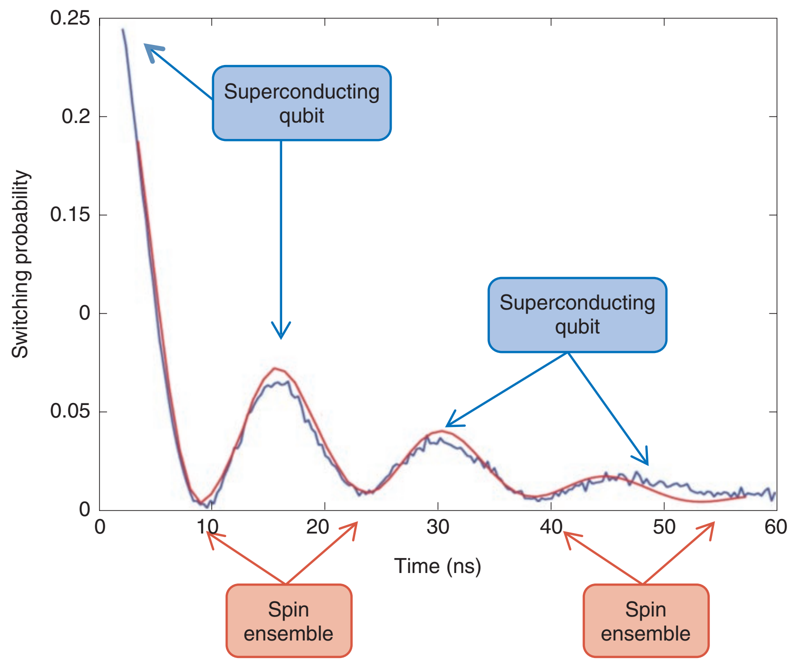


Fig. 8. Vacuum Rabi oscillations between a flux qubit and an NV- spin ensemble.

system. The resulting oscillation with frequency g_{ens} is called a vacuum Rabi oscillation. Finally, to finish the memory operation, we detuned the qubit non-adiabatically away from the spin ensemble (Fig. 7(d)) and read out the qubit state with a dc-SQUID (Fig. 7(e)). The vacuum Rabi oscillations that we observed are shown in **Fig. 8**. The blue (red) curve represents experimental data (simulation). These results indicate that quantum information in the flux qubit was transferred to and then retrieved from the spin ensemble.

7. Concluding remarks

The vacuum Rabi oscillations shown in Fig. 8 continued for only 40 ns, which is much shorter than the decay times of the flux qubit ($T_{2,qb}$ ~ 150 ns) and the NV- spin ensemble ($T_{1,NV}$ >> 10 µs). This indicates an unexpectedly short coherence time for the spin ensemble. There are several likely sources of this dephasing. The most probable is a large electron spin – ½ bath derived from the 100 ppm (parts per million) P1 centers (a nitrogen atom substituting for a carbon atom) present in our diamond crystal. The degeneracy of the $m_s = \pm 1$ states could also be a source of decoherence. Hence, the future challenges are to apply an in-plane magnetic field to remove this degeneracy and to prepare a diamond sample with fewer P1 centers.

In summary, we have experimentally demonstrated strong coherent coupling between a flux qubit and a spin ensemble in a diamond crystal. Furthermore, we have observed the coherent exchange (transfer) of a single quantum of energy between them. This is the first step towards a long-lived quantum memory for a superconducting qubit. It could also lead to an interface between the microwave and optical domains.

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Shiro Saito

Distinguished Researcher, Senior Research Scientist, Superconducting Quantum Physics Research Group, Physical Science Laboratory, NTT Basic Research Laboratories.

He received the B.S., M.S., and Dr.Eng. degrees in applied physics from the University of Tokyo in 1995, 1997, and 2000, respectively. Since joining NTT Basic Research Laboratories in 2000, he has been engaged in quantum information processing research using superconducting circuits. He was a guest researcher at Delft University of Technology, the Netherlands, during 2005–2006. He received the Young Scientist Award from the Japan Society of Applied Physics (JSAP) at the spring meeting in 2004. He is a member of JSAP and the Physical Society of Japan.

Xiaobo Zhu

Senior Research Associate, Superconducting Quantum Physics Research Group, Physical Science Laboratory, NTT Basic Research Laboratories.

He received the Ph.D. degree from the Institute of Physics at the Chinese Academy of Sciences in 2003. During 2003–2008, he worked as an assistant/associate professor in the Institute of Physics at the Chinese Academy of Sciences. He moved to NTT Basic Research Laboratories in Japan in 2008. His research interests include superconducting qubits and circuits and their application in hybrid systems.

William John Munro

Research Specialist Quantum Optical State Control Research Group, Optical Science Laboratory, NTT Basic Research Laboratories.

He received the B.Sc. degree in chemistry and physics in 1989, M.Sc. degree in physics in 1991, and D.Phil. degree in quantum optics in 1994 from the University of Waikato, New Zealand. He entered the computer industry in 1995, where he worked on various projects. In July 1997, he accepted an Australian Research Council Fellowship at the Department of Physics in the University of Queensland. During this fellowship, he developed an interest in entanglement, methods to characterize it, and its practical use in quantum information processing. In 2000, he became a senior researcher in the Australian Special Centre for Quantum Information Processing). In late 2000, he joined HP Labs as a research scientist. In early 2010, he moved to NTT Basic Research Laboratories as a research specialist, where he is working on hybrid-system approaches to both quantum computation and communication. He is currently a visiting professor at the National Institute of Informatics in Japan, the University of Queensland in Australia, and Leeds University in the UK.

Kouichi Semba

Research Professor, Research Support Coordinator, Global Research Center for Quantum Information Science, National Institute of Informatics.

He received the B.S., M.S., and Dr.Eng. degrees from the University of Tokyo in 1983, 1985, and 2002, respectively. He joined the NTT Electrical Communications Laboratories in 1985 and moved to NTT Basic Research Laboratories in 1987. From 2003 to 2012, including the period when the research described in this article was conducted, he was the leader of the superconducting quantum physics research group. He was a visiting researcher in the Department of Nanoscience at Delft University of Technology, the Netherlands, during 2002–2003. He was a lecturer at Waseda University in 2005 and a guest professor at Tokyo University of Science during 2008–2012; he has been a guest professor at the National Institute of Informatics since 2010. His achievements include being the first to characterize the electronic state of Penrose's non-periodic tiling as an ideal 2D-quasicrystal; the first to reveal the relevant elemental composition of the high-Tc cuprate superconductor YBCO (Tc = 90 K); the first to demonstrate entanglement in a solid device, namely vacuum Rabi oscillation in a macroscopic superconducting Josephson-qubit LC-resonator system; and the first to demonstrate the coherent coupling of a superconducting flux qubit and NV spins in diamond.

Theoretical and Experimental Study of Quantum Nondemolition Measurement Using an Electric Circuit

Kosuke Kakuyanagi, Shiro Saito, Hayato Nakano, and Kouichi Semba

Abstract

We are investigating, from both the theoretical and experimental standpoints, how to perform measurements on quantum systems by using an electric circuit that has quantum characteristics. A superconducting flux qubit, which is constructed with a superconducting loop circuit, has discrete energy, so it can be regarded as an artificial atom.

1. Superposition state and its measurement

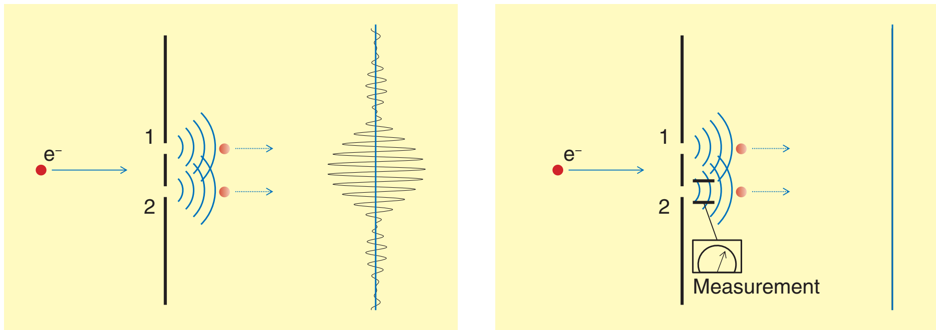
In the quantum world, we can achieve the superposition of several states simultaneously. It is possible to carry out multiple calculations by using a superposition state; therefore, we expect to be able to use it to solve certain types of problems that are difficult to solve with a conventional calculator. An example of a superposition state is shown in **Fig. 1(a)**. A single electron that passes through a double slit exhibits an interference pattern although only one electron reaches the screen because what passes through slits 1 and 2 is a superposition state. If we install an electron detector behind slit 2 to detect which slit the electron passes through, the superposition state disappears and the interference pattern also disappears because the state is decided (**Fig. 1(b)**).

Similar to this phenomenon, a superposition state is stochastically reduced to a state called an eigenstate by measurement (projection). If the electron is not absorbed by the detector and retains its eigenstate after measurement, this measurement is called a quantum nondemolition measurement. How do we deal with a quantum state measurement that appears strange? We use a superconducting flux qubit as an artificial atom and a Josephson bifurcation amplifier (JBA) readout[*1] system, which achieves quantum nondemolition measurement and we study how to perform quantum system measurements both theoretically and experimentally. This study is related to the basic problem of quantum mechanics, namely quantum state measurement. Our goal is to achieve more efficient quantum measurement in the future through an understanding of the mechanism. From a practical point of view, it is important to approach quantum state measurement correctly. Because of the interaction between a qubit and the environment, the qubit coherence, which contains quantum information, gradually decreases. We need quantum error correction to recover this quantum information. We prepare a logical qubit, including an ancillary qubit and a control qubit state that depends on the ancillary qubit's measured state. In the error correction scheme, our control of the quantum state depends on the result of the ancillary qubit measurement. To make quantum algorithms such as error corrections, it is very important to understand the mechanism of quantum measurement.

2. Superconducting flux qubit

In a superconducting loop, the phase of a

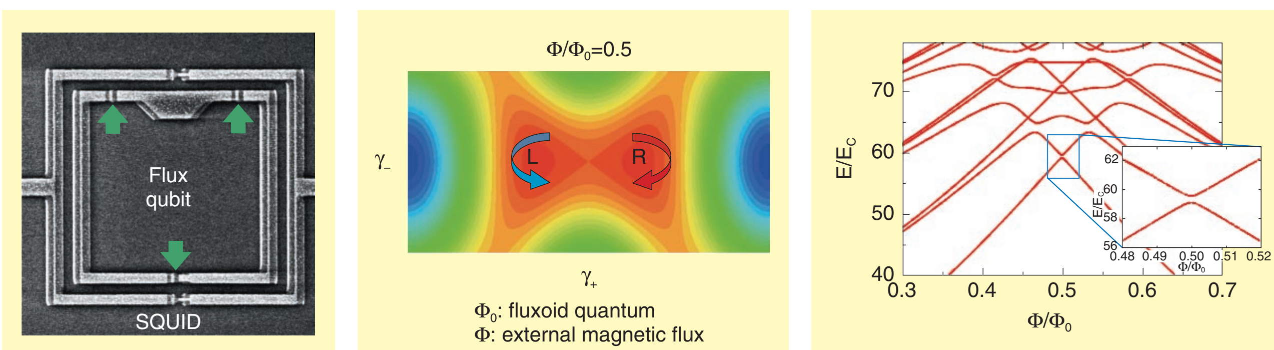
*1 Josephson bifurcation readout method: A method for detecting small displacements by using a bistable state caused by the nonlinearity of a Josephson junction.



(a) Single-electron interference

(b) No interference: disappearance caused by measurement.

Fig. 1. Quantum superposition state and measurement.



(a) Superconducting flux qubit

(b) Double well potential in phase space

(c) Energy diagram of flux qubit

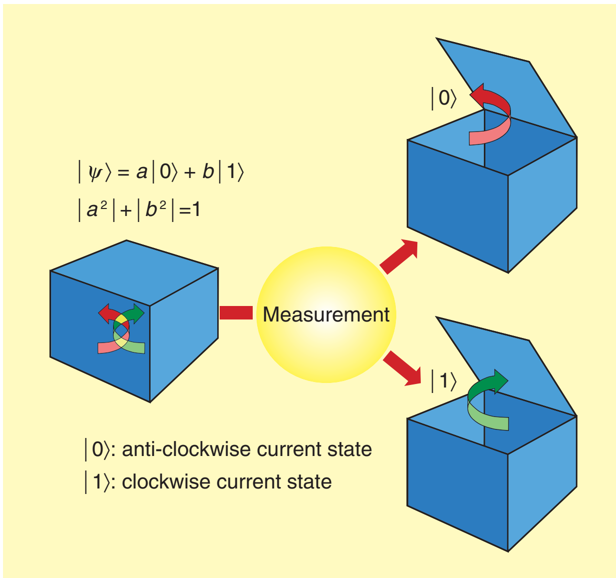
Fig. 2. Superconducting flux qubit as an artificial atom.

superconducting wave function must be continuous, so only discrete magnetic flux values are allowed. If a Josephson junction[*2] is inserted into the loop, a small phase gap is allowed at the junction, so the superconductor phases have time evolution. The energy of a Josephson junction is changed by the junction's phase. Therefore, the energy of the three Josephson junction loops shown in **Fig. 2(a)** have a double well potential in the phase space shown in **Fig. 2(b)**. By using the phases at these junctions γ_1, γ_2, and γ_3, owing to the periodic boundary condition of the phases, we can approximately describe γ_+ and γ_- by $\gamma_+=\gamma_1+\gamma_2$, $\gamma_-=\gamma_3$. Because of the charge energy of a junction, phases trapped at two wells denoted L and R can jump between the wells quantum mechanically. This situation is very similar to that of an electron trapped in the nucleus of an atom. As a result, the energy of a superconducting loop also has discrete energy, as shown in **Fig. 2(c)**, and behaves as an artificial atom. A superconducting flux qubit is a two-level system formed of two of the lowest discrete energy levels of a superconducting loop.

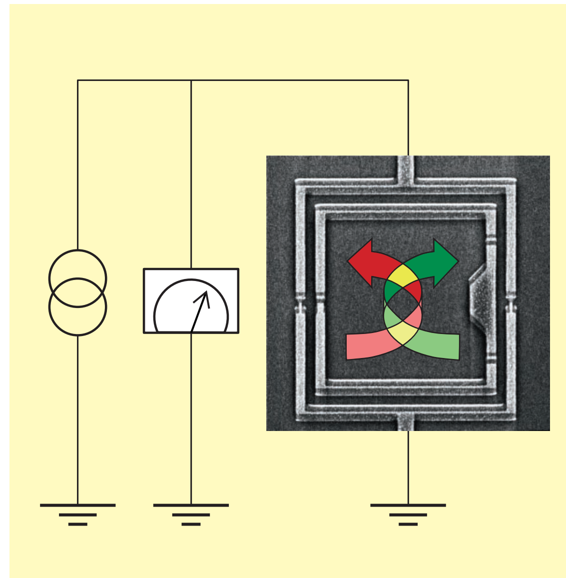
*2 Josephson junction: A junction that exhibits the Josephson effect, which is the phenomenon whereby a supercurrent flows without voltage in a three-layer structure of superconductor, thin insulator, and superconductor.

3. Qubit state measurement

Two minimum energy regions in phase space correspond to the clockwise and anti-clockwise supercurrent states of a superconducting loop. Therefore, the supercurrent direction is different for the qubit ground state and the excited state. A quantum superposition state is achieved in a qubit, so we can achieve the superposition of clockwise and anti-clockwise



(a) Measurement of superposition flux qubit state and state reduction



(b) State detection by SQUID

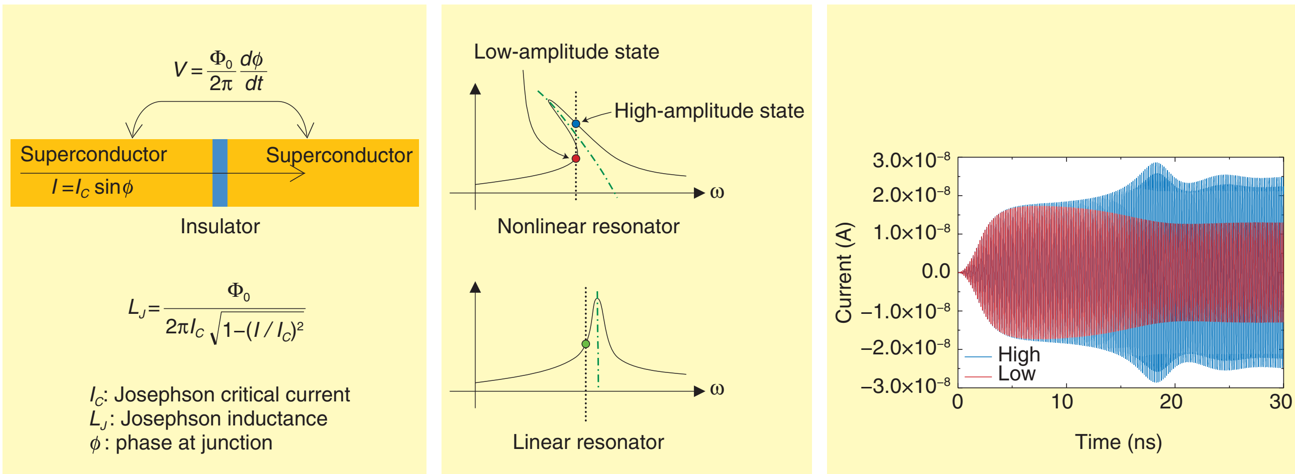
Fig. 3. State measurement of flux qubit.

current states. However, this superposition state is stochastically reduced to an eigenstate by measurement, so the detected state is either the clockwise or anti-clockwise current state (**Fig. 3(a)**). The supercurrent of a superconducting loop generates a small magnetic field. The direction of this magnetic field depends on the superconducting qubit's quantum state; therefore, by detecting this small magnetic field, we can measure the qubit state. A superconducting quantum interference device (SQUID) is used as a device for measuring small magnetic fields. A small current flows in a SQUID without any voltage (superconducting state); however, voltage does appear when the current exceeds the critical current. The critical current of a SQUID is very sensitive to a magnetic field, so we can detect small changes in magnetic field by detecting the voltage of the current flowing in a SQUID near the critical current (**Fig. 3(b)**). This method is easy to use, but the superconducting state is destroyed when the SQUID enters the voltage state, so the qubit state is also destroyed. Therefore, we can detect the qubit state, but one more measurement does not reproduce the qubit state. This means that we have no information about the destroyed qubit state. Therefore, we need to develop a new measurement technique that does not destroy the quantum information.

4. Nonlinear bifurcation

A Josephson junction works as an inductor in electric circuits, as shown in **Fig. 4(a)**. Unlike a conventional inductor, the Josephson junction exhibits nonlinear characteristics as the applied current is increased. When we drive a nonlinear resonator that includes a Josephson junction, the junction's inductance increases with increasing driving current. Consequently, the resonance frequency shifts to a lower frequency. When we drive the resonator at a frequency slightly lower than the base resonance frequency, a bistable state appears. One stable state is a low-amplitude state and the other is a high-amplitude state, which is frequency-shifted owing to nonlinearity (**Fig. 4(b)**). If an external driving current is applied, the resonance state will converge to either the low- or high-amplitude state over time (**Fig. 4(c)**). The stable state that appears is sensitively dependent on the resonator parameters.

By driving near the bistable state's boundary, we can detect a small difference in a system that is coupled to a resonator as a difference in the resonator's resonance state. When we establish a magnetic coupling between a resonator and a superconducting qubit and drive in the optimum microwave condition, we can detect the qubit state by checking whether the JBA resonator is in the high- or low-amplitude state.



(a) Josephson junction as a nonlinear inductance

(b) Resonance curves of linear and nonlinear resonators

(c) Driven nonlinear resonator

Fig. 4. Characteristics of nonlinear resonator.

In this case, the superconducting circuit remains in the superconducting state, so the qubit quantum state is more difficult to break when this readout method is used than when the switching readout method is used. This method is called the JBA readout method.

5. Strength of measurement and projection to eigenstate

With the JBA readout method, we drive a nonlinear resonator with a readout microwave and read the quantum state. How does the projection from a superposition state to an eigenstate occur? We studied when the projection occurred by changing the readout pulse height.

First, we prepared a qubit superposition state and applied a short readout pulse. By using a gate operation, we can reproduce the previous state in the case of a superposition state. However, a mixed state after projection generally does not change to the previous state as the result of a gate operation. So we read the qubit state after a gate operation: from the readout pulse, we can know whether or not projection has occurred. To modify the measurement strength, we change the amplitude of the readout pulse and measure it. As a result, the α value, which indicates projection to the eigenstate, suddenly becomes 0 as the readout pulse increases (**Fig. 5**). This result means that projection does not occur ($|\alpha| \neq 0$) when the measurement is weak, and sudden projection ($|\alpha| = 0$) occurs if the measurement strength reaches a critical value.

6. Theoretical analysis of measurement

It is easy to construct a theoretical model of the JBA measurement system for comparison with other systems because a JBA measurement system consists of only a nonlinear resonator and a coupled qubit.

We analyzed the JBA measurement system theoretically on the basis of this model. As a result, we confirmed that the superposition state of a qubit interacts with a JBA resonator through an applied readout pulse, and the qubit and JBA resonator form a quantum-entangled state as a result of time evolution. This quantum entangled state achieves the superposition of (1) a qubit ground state and a JBA low-amplitude state and (2) a qubit excited state and a JBA high-amplitude state. Owing to the time evolution of this quantum system, the entangled state is suddenly destroyed by decoherence and is stochastically convergent to one of the two states. These are our predictions for measurement based on theoretical analysis. This measurement analysis corresponds to the sudden projection into the eigenstate that we observed in our experiment when we increased the measurement amplitude, so this phenomenon strongly supports the validity of our theoretical analysis of measurement in a JBA system.

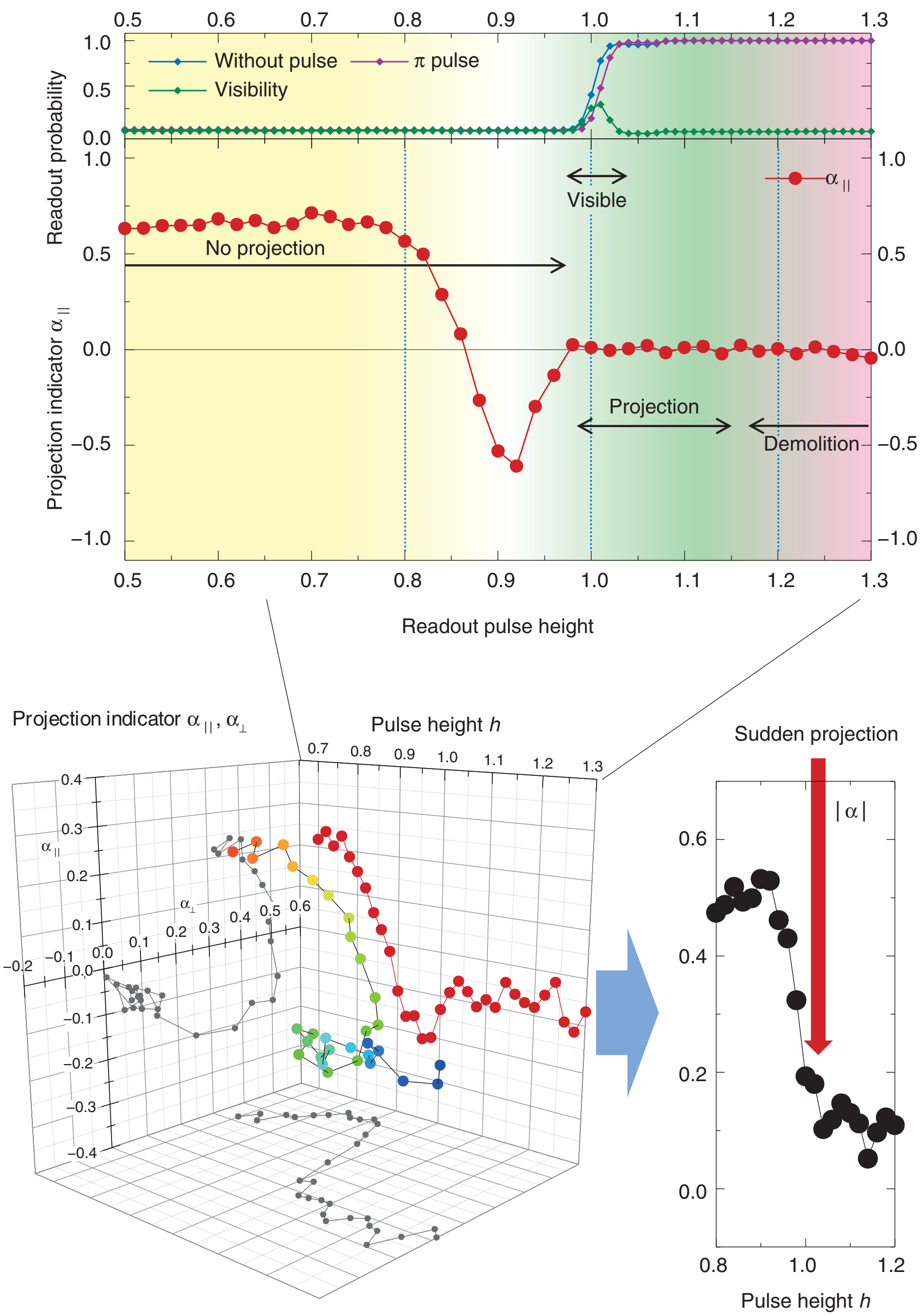
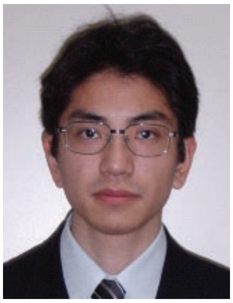


Fig. 5. Measurement strength and projection.

7. Future prospects

Our understanding of how to measure a superconducting flux qubit with the JBA measurement process has progressed. By using this knowledge, we aim to achieve fast measurement and control of quantum states with high accuracy toward the achievement of quantum error correction, which will be essential for quantum computing in the future.



Kosuke Kakuyanagi

Researcher, Superconducting Quantum Physics Research Group, NTT Basic Research Laboratories.

He received the B.S., M.S., and Ph.D. degrees in science from Hokkaido University in 2000, 2002, and 2005, respectively. He joined NTT Basic Research Laboratories in 2005 and has been studying superconducting qubits. He is currently engaged in an experimental study of a Josephson bifurcation readout method. He is a member of the Physical Society of Japan (JPS) and the Japan Society of Applied Physics (JSAP).

Shiro Saito

Distinguished Researcher, Senior Research Scientist, Superconducting Quantum Physics Research Group, Physical Science Laboratory, NTT Basic Research Laboratories.

He received the B.S., M.S., and Dr.Eng. degrees in applied physics from the University of Tokyo in 1995, 1997, and 2000, respectively. Since joining NTT Basic Research Laboratories in 2000, he has been engaged in quantum information processing research using superconducting circuits. He was a guest researcher at Delft University of Technology, the Netherlands, during 2005–2006. He received the Young Scientist Award from JSAP at the spring meeting in 2004. He is a member of JPS and JSAP.

Hayato Nakano

Research Scientist, Superconducting Quantum Physics Research Group, NTT Basic Research Laboratories.

He received the B.E. and M.E. degrees in communication engineering from Osaka University in 1983 and 1985, respectively and the Ph.D. degree in applied physics from Hokkaido University in 1997. He joined NTT Ibaraki Electrical Communications Laboratories in 1985 and studied fiber optics. From 1987, he was engaged in solid-state quantum physics in NTT Basic Research Laboratories. In 2004, he was a guest researcher at Scuola Normale Superiore in Pisa, Italy, studying geometrical quantum computations. During 2007–2010, he was a guest professor of quantum information at Nara Advanced Institute of Science and Technology (NAIST). He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), JPS, and the European Physical Society.

Kouichi Semba

Research Professor, Research Support Coordinator, Global Research Center for Quantum Information Science, National Institute of Informatics.

He received the B.S., M.S., and Dr.Eng. degrees from the University of Tokyo in 1983, 1985, and 2002, respectively. He joined the NTT Electrical Communications Laboratories in 1985 and moved to NTT Basic Research Laboratories in 1987. From 2003 to 2012, including the period when the research described in this article was conducted, he was the leader of the superconducting quantum physics research group. He was a visiting researcher in the Department of Nanoscience at Delft University of Technology, the Netherlands, during 2002–2003. He was a lecturer at Waseda University in 2005 and a guest professor at Tokyo University of Science during 2008–2012; he has been a guest professor at the National Institute of Informatics since 2010. His achievements include being the first to characterize the electronic state of Penrose's non-periodic tiling as an ideal 2D-quasicrystal; the first to reveal the relevant elemental composition of the high-Tc cuprate superconductor YBCO (Tc = 90 K); the first to demonstrate entanglement in a solid device, namely vacuum Rabi oscillation in a macroscopic superconducting Josephson-qubit LC-resonator system; and the first to demonstrate the coherent coupling of a superconducting flux qubit and NV spins in diamond.

Electron Spin Rotation and Quantitative Determination of Spin-Orbit Coefficients

Takaaki Koga and Yoshiaki Sekine

Abstract

In recent research, there have been proposals to realize quantum bits (qubits) with electron spins, where these qubits compose a quantum computer. In this article, we explain the mechanism of electron spin precession that is caused by the Rashba spin-orbit interaction and introduce the latest research results on quantitative determination of the Rashba and Dresselhaus spin-orbit coefficients. These findings represent a step toward the utilization of electron spins as qubits of a quantum computer.

1. Background

1.1 Spin in conventional electronic devices

An electron has not only a *charge* degree of freedom but also a *spin* degree of freedom associated with the spin angular momentum. If a charged particle has angular momentum, magnetic moment is generated. Therefore, each electron, having a spin angular momentum, acts as a micromagnet. The spin degree of freedom can be interpreted, in one way, as the freedom in the orientation of the micromagnet. In other words, spin is not a conserved quantity. Thus, it has not been easy to use them in conventional devices. Recently, research on electron spin in semiconductors has become increasingly important because future technologies that will transcend existing concepts, such as quantum computers based on spin qubits, will be based on current basic research such as the fundamental research studies described in this article.

1.2 Spin and magnetic moment

While spin is naively interpreted as a micromagnet, its quantum mechanical properties are complicated and the spin sometimes behaves contrary to everyday experience. For example, one would associate the word *spin* with the spin of a tennis ball, where the magnitude of the ball's angular momentum can be varied continuously by applying a torque. However, the *spin* of an electron cannot be varied continuously. To describe such peculiar properties of electron spin, we dare to provide a quantum mechanical explanation of electron spin in this article.

1.3 The Stern-Gerlach experiment

The fact that the magnitude of electron spin is not continuously variable but takes only discrete values was confirmed by the Stern-Gerlach experiment (**Fig. 1**) [1]. While tiny particles of silver were used in the actual experiment, the experimental results reflect the properties of electron spin. When electrons pass through space containing a magnetic field whose magnitude is graded in the perpendicular direction, their spins are decoupled into two states with different magnetic moments, as if they have been sorted (taking a bar magnet as an example, these are an up-spin state with the south (S) magnetic pole facing upward and a down-spin state with the S pole facing downward). A straightforward interpretation of the measured results leads to the conclusion that the magnetic moment of electron spins can take only two values: either the value corresponding to the upward direction or the value corresponding to the downward direction. Then, might there be electrons with a spin state that is neither upward nor downward vertically, such as those whose S pole is pointing horizontally among the electrons that have passed through the detector? To give the conclusion first: yes, there are

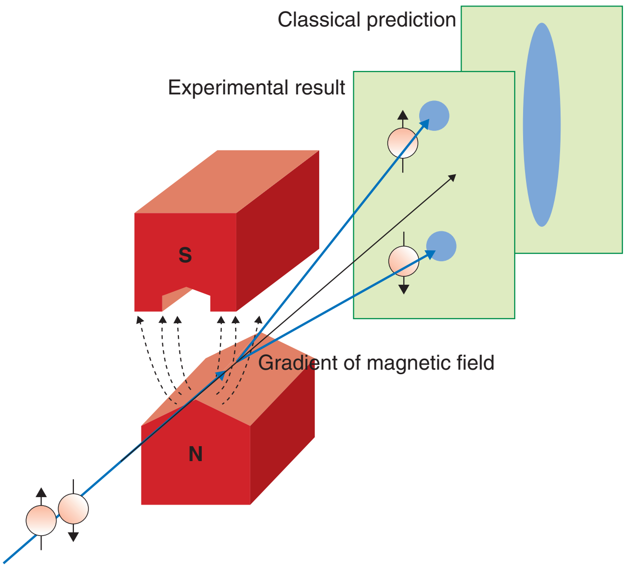


Fig. 1. Stern-Gerlach experiment.

such electrons. To understand why and to make correct predictions about spin-related phenomena in semiconductor devices, we need an accurate understanding of quantum mechanics.

1.4 Probability interpretation of the wave function and reduction of the wave packet

Two well-known concepts in quantum mechanics are probability interpretation (of the wave function) and reduction of the wave packet. Considering a one-dimensional world for simplicity, let us express the wave function of an electron by $\Psi(x)$.

Probability interpretation means the following. When we try to measure the location of an electron described by $\Psi(x)$, the probability that the electron is found at a position between x and $x+\Delta x$ is given by $|\Psi(x)|^2\Delta x$. Reduction of the wave packet is related to probability interpretation. It is a term that describes how an electron in a state with a wide probabilistic distribution $|\Psi(x)|^2$ (wave packet) before measurement collapses to a point at a certain position x as a consequence of the measurement.

1.5 Spin states other than up and down

Besides an electron's position, its spin state is also more correctly described by a wave function. If we apply the concept of reduction of the wave packet, then the Stern-Gerlach experiment is interpreted as the collapse of the wave function of electron spin to either an up state or a down state by measurement. We note that the up/down direction is the direction of the magnetic field (z direction) within the experimental apparatus (detector).

Since we have freedom in the direction of the magnetic field to be set in the detector of the experimental apparatus, we can also select any arbitrary direction for the observation of a magnetic moment. We would like to emphasize that the phenomena we are explaining here are not related to the torque that the magnetic field in the detector may apply to the electron spin to change its orientation. We are saying that the orientation of the spin is varied as a result of the reduction of the wave packet.

To understand the above description, one needs to know that any state (wave function) of electron spin is described by a wave function $a|\uparrow\rangle_z + b|\downarrow\rangle_z=\begin{pmatrix}a\\b\end{pmatrix}$, which is a superposition of the up-spin $\begin{pmatrix}1\\0\end{pmatrix} \equiv |\uparrow\rangle_z$ and down-spin $\begin{pmatrix}0\\1\end{pmatrix} \equiv |\downarrow\rangle_z$ wave functions. One needs to accept the quantum mechanical conclusion that the probabilities of observing the up- and down-spin states upon measurement of spin state $a|\uparrow\rangle_z + b|\downarrow\rangle_z=\begin{pmatrix}a\\b\end{pmatrix}$ are given by $|a|^2$ and $|b|^2$, respectively, where a and b are complex numbers such that $|a|^2 + |b|^2 = 1$. Moreover, if we perform the measurements on the same spin state $a|\uparrow\rangle_z + b|\downarrow\rangle_z=\begin{pmatrix}a\\b\end{pmatrix}$ while varying the direction of the magnetic field in the detector, we will find a certain direction for which observation of only up-spin electrons will result (up-spin with respect to the chosen magnetic field direction). This direction is called the direction (or orientation) of the electron spin. Generally, electron spin orientations differ from one electron to another. However, the conclusion of quantum mechanics is that any electron spin can be expressed as $a|\uparrow\rangle_z + b|\downarrow\rangle_z$ by finding appropriate complex numbers a and b, whichever direction it is pointing in.

From the above discussion, we can conclude the following. If there are two spin states $|\uparrow\rangle_x$ and $|\downarrow\rangle_x$ that are orientated in the $+x$ and $-x$ directions, respectively, we should be able to write them as a superposition of $|\uparrow\rangle_z$ and $|\downarrow\rangle_z$, which ultimately leads to $|\uparrow\rangle_x=\frac{1}{\sqrt{2}}\left(|\uparrow\rangle_z + |\downarrow\rangle_z\right)$ and $|\downarrow\rangle_x=\frac{1}{\sqrt{2}}\left(|\uparrow\rangle_z - |\downarrow\rangle_z\right)$. If we interpret this probabilistically, then the probability that a spin-up or spin-down state is detected (with respect to the z direction) is 50% upon the measurement of these spins. Conversely, the state $a|\uparrow\rangle_z + b|\downarrow\rangle_z$ can also be written as $\frac{(a+b)}{\sqrt{2}}|\uparrow\rangle_x + \frac{(a-b)}{\sqrt{2}}|\downarrow\rangle_x$ using $|\uparrow\rangle_x$ and $|\downarrow\rangle_x$. Therefore, if the direction of the magnetic field in the detector is in the x direction, the up- and down- spin states will be observed with probabilities $\frac{|a+b|^2}{2}$ and $\frac{|a-b|^2}{2}$, respectively.

We finally ask which direction is the electron spin $a|\uparrow\rangle_z + b|\downarrow\rangle_z$ pointing in? We provide only the conclusion here. The three-dimensional vector for the orientation of this spin is $(x, y, z) = (2\mathrm{Re}(a^*b), 2\mathrm{Im}(a^*b), |a|^2 - |b|^2)$, where $\mathrm{Re}(a^*b)$ and $\mathrm{Im}(a^*b)$ are the real and imaginary parts of the complex number a^*b, respectively.

1.6 Spin splitting due to the Rashba effect

In our research, we use a spin-orbit interaction called the Rashba effect [2] in controlling electron spins. A Hamiltonian*1 of the spin-orbit interaction generally takes the form $(\nabla V \times \mathbf{p}) \cdot \sigma$. Using the confinement potential $V(z)$ of the quantum well for V, i.e., $\nabla V(z) = (0, 0, -eE_z)$, and $\hbar\mathbf{k}$ for $\mathbf{p}$ (momentum), we obtain the Hamiltonian for the Rashba effect as $H_R = a_{so} \langle E_z \rangle (k_y\sigma_x - k_x\sigma_y)$. Here, a_{so} is a material-dependent intrinsic constant for the Rashba effect, $\langle E_z \rangle$ is the expectation value of E_z, and σ_x and σ_y are the Pauli spin matrices.*2 If we use a plane wave for the orbital part of the wave function for simplicity with a two-dimensional wave vector $\mathbf{k} \equiv (k_x, k_y) = (k, 0)$, the wave functions (eigenfunctions) including the spin part are given by $\frac{e^{ikx}}{\sqrt{2}}\begin{pmatrix} i \\ \mp 1 \end{pmatrix}$ with respective eigenenergies $\frac{\hbar^2 k^2}{2m^*} \pm a_{so}\langle E_z \rangle k$. Thus, the energy splitting between the two states $\frac{e^{ikx}}{\sqrt{2}}\begin{pmatrix} i \\ \mp 1 \end{pmatrix}$ at a constant wave vector, which is caused by a spin-orbit interaction associated with the confinement potential of semiconductor heterostructures, is called the Rashba splitting*3 (**Fig. 2**).

*1 Hamiltonian: Operator that provides a physical quantity corresponding to energy in quantum physics.

*2 Pauli spin matrices: Three matrices $\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, $\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$, and $\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ used to describe the spin angular momentum in quantum mechanics, and a vector form of them, i.e., $\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$.

*3 Rashba splitting: Spin splitting in the energy dispersion relation of an electron that is caused by the Rashba spin-orbit coupling effect.

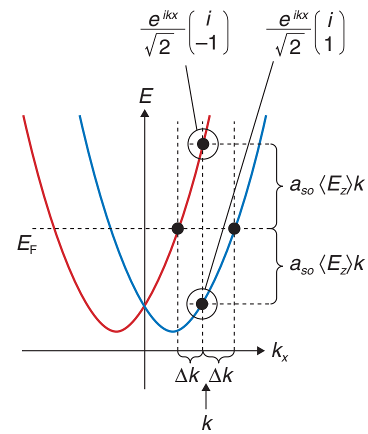


Fig. 2. Energy dispersion of two-dimensional electron system with the Rashba splitting.

1.7 Spin rotation

Consider a superpositioned wave function $\frac{e^{i(k-\Delta k)x}}{2}\begin{pmatrix} i \\ -1 \end{pmatrix} + \frac{e^{i(k+\Delta k)x}}{2}\begin{pmatrix} i \\ 1 \end{pmatrix} = ie^{ikx}\begin{pmatrix} \cos(\Delta kx) \\ \sin(\Delta kx) \end{pmatrix}$ that is composed of two wave functions associated with two points on the Fermi surface*4 $(k \pm \Delta k, 0)$, where $\Delta k = a_{so}\langle E_z \rangle m^*/\hbar^2$, in a system having the Rashba splitting. The spin part of this wave function at $x = 0$ is $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$, where the spin is orientated in the z direction. The electron spin states for $x \neq 0$ are $\begin{pmatrix} \cos(\Delta kx) \\ \sin(\Delta kx) \end{pmatrix} = \cos(\Delta kx)\begin{pmatrix} 1 \\ 0 \end{pmatrix} + \sin(\Delta kx)\begin{pmatrix} 0 \\ 1 \end{pmatrix}$, the spin orientation of which is $(\sin(2\Delta kx), 0, \cos(2\Delta kx))$ in a three-dimensional vector. Thus, the spin rotates in the x-z plane as a function of the electron's position x. An electron in a semiconductor can be regarded as a wave packet having a central wave number. Since the propagation speed of a wave packet is given by its group velocity (Fermi velocity) $\frac{\hbar k}{m^*}$, an electron in uniform linear motion changes its position according to its Fermi velocity. Thus, the spin orientation will rotate accordingly. The angular velocity of the electron spin

*4 Fermi surface: Curved surface in the wave number space (k-space) defined by $E(\mathbf{k}) = E_F$, where $E(\mathbf{k})$ is the band energy dispersion of an electron in a solid and E_F is the Fermi energy. Regions in k-space that have energies lower than E_F are filled with electrons. The electron transport properties of a solid are usually closely related to the properties of the Fermi surface including its shape and how it interacts with phonons and impurities.

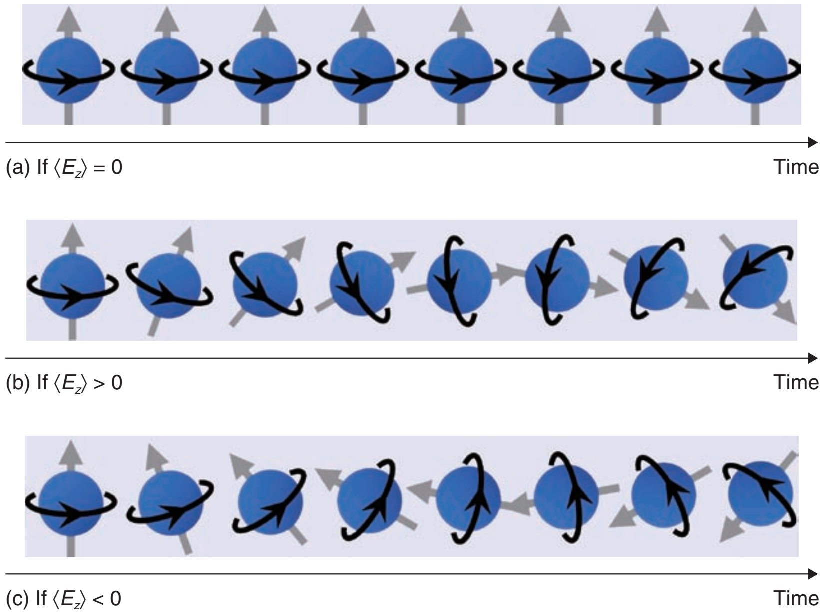


Fig. 3. Examples of spin precession.

rotation is given as $\omega = 2a_{so}\langle E_z\rangle k/\hbar$ in this case. The tunability of $\langle E_z\rangle$ by an external gate or a specific design of the heterostructure enables us to control the angular velocity of spin rotation, which is one of the greatest attractions of the Rashba effect. Some examples of spin rotation for an electron moving at the Fermi velocity are shown in **Fig. 3**, where a_{so} acts as a parameter indicating how easy it is to control the electron spin precession by an electric field $\langle E_z\rangle$.

In research on the Rashba effect up to now, it has been important to obtain a value called the Rashba coefficient α, which corresponds to $a_{so}\langle E_z\rangle$. Pieces of circumstantial evidence showing that the α values are controllable by a gate had been accumulated, though nobody had been able to show a quantitatively linear relationship between α and $\langle E_z\rangle$. The factors that have delayed the progress of this research include (1) a lack of experimental methods that enable one to measure the value of $\langle E_z\rangle$ within a quantum well directly and (2) uncertainty about the size of the Dresselhaus spin splitting (the spin splitting arising from the bulk inversion asymmetry), which coexists with the Rashba spin splitting. In collaborative work between Hokkaido University and NTT Basic Research Laboratories, we have demonstrated the linear relationship $\alpha = a_{so}\langle E_z\rangle$ quantitatively by using $In_{0.53}Ga_{0.47}As$ semiconductor quantum wells (**Fig. 4**), which are lattice-matched to (001) InP; this led to the successful quantitative determination of the value of a_{so} [3]. A key to our success was the coincidental discovery of an epitaxial wafer that has the property that the value of $\langle E_z\rangle$ can seemingly be varied from positive to negative values by means of gating. Careful experiments with this epitaxial wafer and a series of similar wafers resulted in our quantitative determination of a_{so}.

2. Latest results

2.1 Experimental procedure for determining a_{so}

The testpiece used in our experiment was a 10-nm-thick $In_{0.53}Ga_{0.47}As$ semiconductor quantum well grown on the (001) plane of an InP substrate (with barrier layers of $In_{0.52}Al_{0.48}As$). We controlled the electron density and the perpendicular electric field $\langle E_z\rangle$ within the quantum well by means of a surface gate in a field-effect-transistor structure (Fig. 4). We used a dilution refrigerator to cool the sample down to ~100 mK (electron temperature), in order to minimize the effect of thermal disturbance and increase the measurement sensitivity, and measured the electric resistance as a function of the perpendicular magnetic field (magneto-resistance) for various gate voltages. In these measurements, a distinctive phenomenon called the *weak antilocalization* appeared in the vicinity of zero magnetic field, owing to the

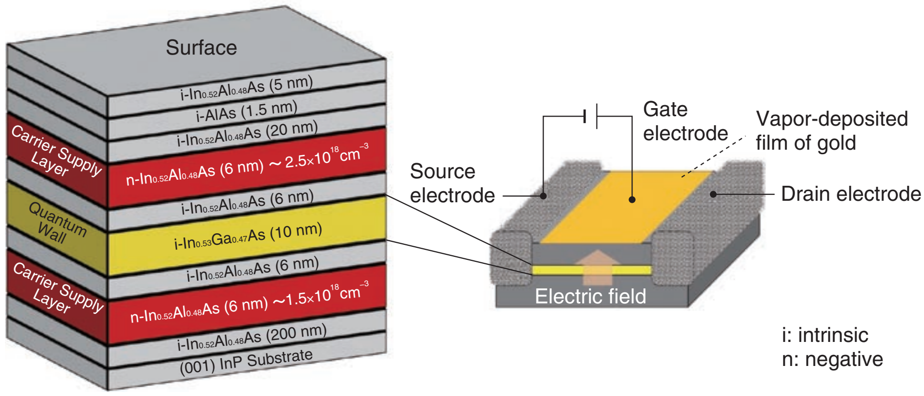


Fig. 4. Experimental sample and FET structure.

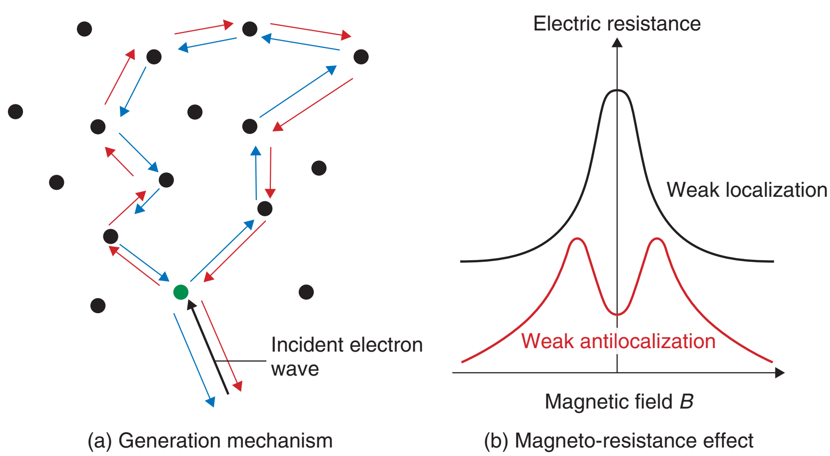


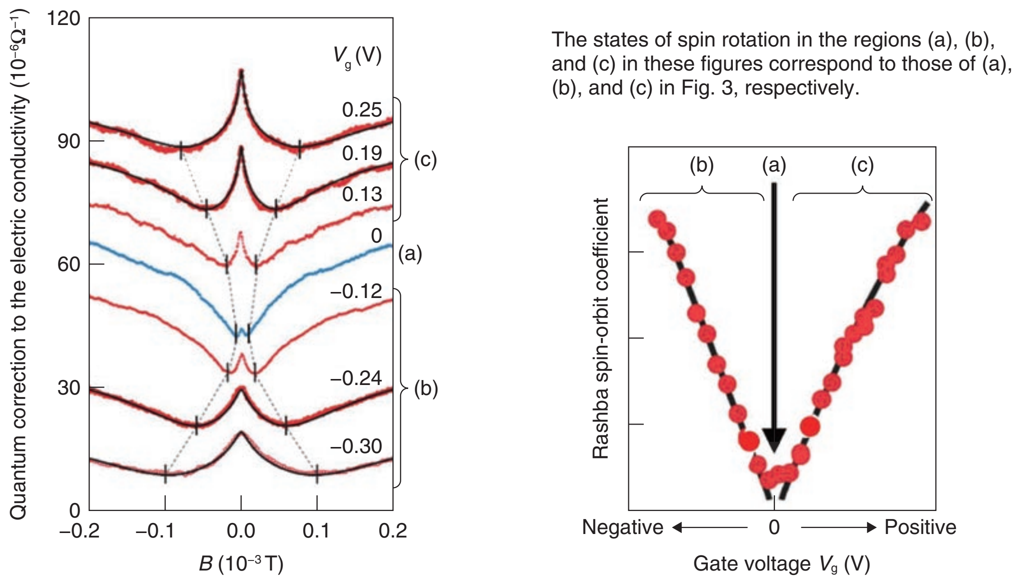
Fig. 5. Weak localization and weak antilocalization effects.

interference of the electron wave functions. We were able to determine the value of the Rashba coefficient α by theoretically analyzing this experimentally observed phenomenon [4].

2.2 Weak localization and weak antilocalization effects

Weak localization is a phenomenon that occurs when an electron is scattered sequentially in a loop by impurities distributed randomly in the conductor, whereby the electrons are weakly localized in the loop as a result of constructive interference of the wave functions. For example, if an electron happens to follow the closed path indicated by blue arrows in **Fig. 5(a)** after the injection of the electron as indicated by the black arrow, then the red path, which is the time-reversed path of the blue one, should also be present quantum mechanically with the same probability as the blue path. Since the lengths of the two paths are exactly equal, constructive interference always occurs at the endpoint of the two paths (the position of the green impurity in Fig. 5(a)), if the electron propagation is not accompanied by spin rotation. This results in enhancement of the backscattering probability. This is the mechanism of weak localization.

The weak localization effect is partially destroyed if a magnetic field is applied perpendicular to the quantum well. As a result, a negative magneto-resistance appears in the vicinity of the zero magnetic field, as shown by the black curve in **Fig. 5(b)**. The *weak localization* effect observed in the vicinity of



(a) Experimental results

(b) Gate voltage dependence of the Rashba coefficient α.

Fig. 6. Measurement of weak localization and weak antilocalization.

zero magnetic field is also suppressed by the rotation of spins, which is called *weak antilocalization*. In a more precise description, the mechanism of the *weak antilocalization* is related to the non-commutativity of spin rotation operators (AB ≠ BA for arbitrarily chosen A and B). This results in a positive magneto-resistance if the *weak antilocalization* is occurring (the red curve in Fig. 5(b)).

The results of our experiment are shown in **Fig. 6(a)**, where the electric conductivity of a quantum well sample is plotted (on the vertical axis) as a function of the magnetic field (horizontal axis) for various values of the gate voltage Vg. It is necessary to invert the + and - signs on the vertical axis (or invert up and down) when comparing the results with the schematic weak localization/antilocalization effects shown in Fig. 5(b) because the data plotted here are the electric conductances, not the resistances. Because V_g is a relative quantity, its value is set to 0 V when the Rashba splitting is minimized in this analysis. This experimental result shows that the weak antilocalization effect becomes stronger as the absolute value of Vg increases. Then, the value of the Rashba coefficient α can be extracted from the values of the fitting parameters that fit the experimental result best assuming a recently developed theoretical model. The gate voltage dependence of the Rashba spin-orbit interaction coefficient α of this sample obtained from such analyses is shown in **Fig. 6(b)**. We note that the angular velocity of the electron spin rotation rises faster as α increases. The fact that we successfully made accurate predictions of the values of α as a function of the gate voltage V_g as in Fig. 6(b) indirectly means that we succeeded in controlling the angular velocity of the electron spin rotation freely by means of the gate of a transistor. For example, we can rotate the spins of electrons within a semiconductor about some specific axis ((b) in Fig. 3), halt the rotation ((a) in Fig. 3), and rotate them in reverse ((c) in Fig. 3) all by means of a gate. As a result, we expect that the knowledge acquired in this research will bring us one step closer to being able to utilize electron spins in future electronic devices such as quantum computers and ultra-low-power logic devices.

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Takaaki Koga
Associate Professor, Graduate School of Information Science and Technology, Hokkaido University.

He received the B.S. degree in engineering from the University of Tokyo in 1992 and the M.S. and Ph.D. degrees in applied physics from Harvard University, USA, in 1995 and 2000, respectively. He joined NTT Basic Research Laboratories as a research associate in 2000 and studied semiconductor spintronics. In 2004, he moved to Hokkaido University as an associate professor. He is currently engaged in an experimental study of spin-orbit interaction in semiconductors. He is a member of the American Physical Society, the Physical Society of Japan (JPS), and the Japan Society of Applied Physics (JSPA).

Yoshiaki Sekine
Researcher, Spintronics Research Group, NTT Basic Research Laboratories.

He received the B.S. degree in engineering from Hokkaido University in 1994 and the M.S. and Ph.D. degrees in science from the University of Tokyo in 1996 and 1999, respectively. He joined NTT Basic Research Laboratories in 1999 and has been studying semiconductor spintronics. He is currently engaged in an experimental study of spin-orbit interaction in semiconductors. He is a member of JPS and JSPA.

Quantum Simulation with Ultracold Atomic Gases in an Optical Lattice

Makoto Yamashita and Kensuke Inaba

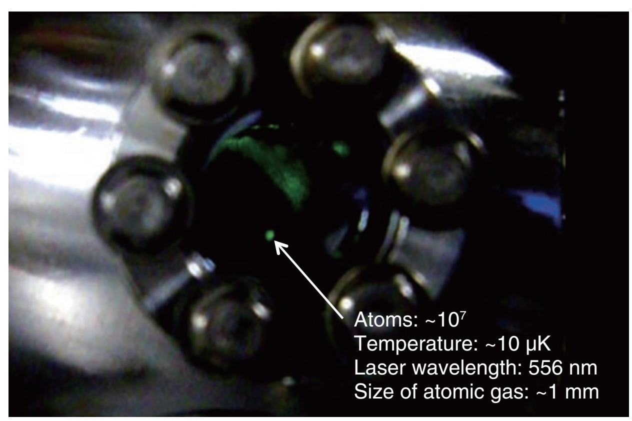
Abstract

In this article, we review quantum simulation for exploring various properties of matter via ultracold atomic gases at nanokelvin temperatures confined in an optical lattice, which is an artificial crystal created by laser lights. We also explain our recent research conducted in collaboration with Kyoto University. Novel quantum states of matter have been successfully achieved for the first time by using ultracold ytterbium atoms in optical lattices.

1. Introduction

In order to explore various properties of matter, we are studying quantum simulation by using ultracold atomic gases at nanokelvin temperatures confined in an optical lattice, which is an artificial crystal created by laser lights. We can introduce our research using the photograph shown in **Fig. 1**. The green spot at the center indicated by the arrow corresponds to a cold gas of ytterbium atoms emitting fluorescence during laser cooling in the ultrahigh vacuum chamber. This atomic gas is about 1 mm in diameter and contains about ten million ytterbium atoms; the temperature is of the order of 10 μK. An advanced experimental technique based on evaporative cooling has succeeded in further lowering the gas temperature by four orders of magnitude and achieving ultracold atomic gases at temperatures of a few nanokelvins. Such gases are considered to be the coldest matter on earth and they obey laws of physics that are contrary to the common sense that we use in our daily lives, namely they obey quantum mechanics.

A new approach for studying fundamental problems in quantum mechanics via ultracold atomic gases has recently been attracting many researchers' interest. One can simulate complicated quantum mechanical phenomena in a well-controlled manner by utilizing the highly controllable atoms available at extremely low temperatures. This approach is therefore referred to as *quantum simulation* [1].



Photograph by Dr. Seiji Sugawa, Kyoto University

Fig. 1. Cold atomic gas of ytterbium confined in an ultrahigh vacuum chamber.

We know that quantum mechanical effects cause various phenomena found in condensed matter, e.g., the metallic, insulating, magnetic, and superconducting properties of materials. Some of them, however, are highly complicated, so it is still very difficult to obtain a full theoretical understanding of their properties even using supercomputers. A typical example is that the mechanism of high-temperature superconductivity has not yet been completely clarified thirty years after its discovery. We can expect these unresolved problems in condensed matter physics to be solved in the near future through quantum simulation using ultracold atomic gases.

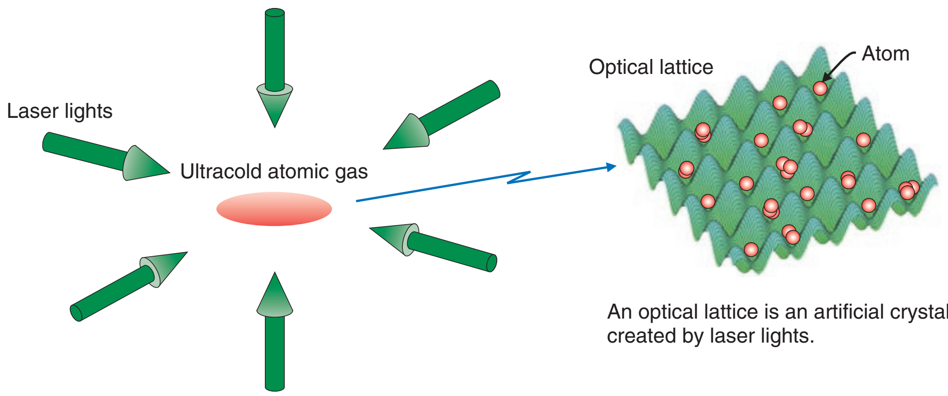


Fig. 2. Schematics of an optical lattice.

On the other hand, experimental techniques for measuring and manipulating single atoms are showing rapid progress, providing us with promising future applications of atomic gases in quantum technologies. One of the final targets is to construct a quantum computer in which each single atom works as a quantum bit. NTT Basic Research Laboratories has been exploring the enormous potential ability of ultracold atoms both theoretically and experimentally [2].

In this article, we review quantum simulation with ultracold atomic gases and then explain our recent research that has successfully demonstrated the novel quantum state of matter using ytterbium atoms in collaboration with Professor Yoshiro Takahashi's group at Kyoto University [3].

2. Optical lattice: artificial crystal created by laser lights

An optical lattice is one of the key experimental techniques for quantum simulation based on ultracold atomic gases. We create an optical lattice by applying counterpropagating laser lights to the ultracold cold atomic gas, as schematically depicted in **Fig. 2**. Here, the laser light wavelength is greatly detuned and is far from the resonance wavelength of the atoms. In this situation, the atoms do not absorb laser photons; hence, heating of the atoms does not occur. The counterpropagating laser lights form a standing wave so as to produce a lattice-like potential that changes periodically with spatial position. An optical lattice corresponds to this periodic potential with atoms confined inside. When laser lights illuminate an atomic gas from six directions, as shown in Fig. 2, the lattice structure becomes a simple cubic one and the lattice distance is exactly equal to half the laser wavelength.

The right diagram in Fig. 2 shows a view of atoms confined on a certain plane in the cubic optical lattice. Atoms move around in the periodic lattice potential by means of quantum tunneling and they interact with each other when multiple atoms coexist at the same lattice site. From this diagram, we understand that an optical lattice acts as an artificial crystal created by laser lights, and confined atoms behave just like electrons in solids. If highly stabilized lasers are used, this optical lattice becomes an ideal crystal without any influence from lattice vibrations, lattice defects, or impurities. Furthermore, the potential depth of an optical lattice changes depending on the laser intensity, which enables the dynamical motion of atoms in this artificial crystal to be controlled via the lasers. Through the development of optical lattices, research on ultracold atomic gases has now become closely related to condensed matter physics.

3. Bosons and fermions

In quantum mechanics, all particles are classified into two kinds of fundamental particles according to their quantum statistics: bosons (bosonic particles) and fermions (fermionic particles). Their energy distributions at the temperature of absolute zero are shown in **Fig. 3**. Bosons have the property that any number of them can occupy a single energy level. Familiar examples of bosons are photons and helium atoms (mass number: 4). Moreover, superfluidity, which is exhibited by liquid helium at low temperatures, is attributed to the bosonic nature of helium

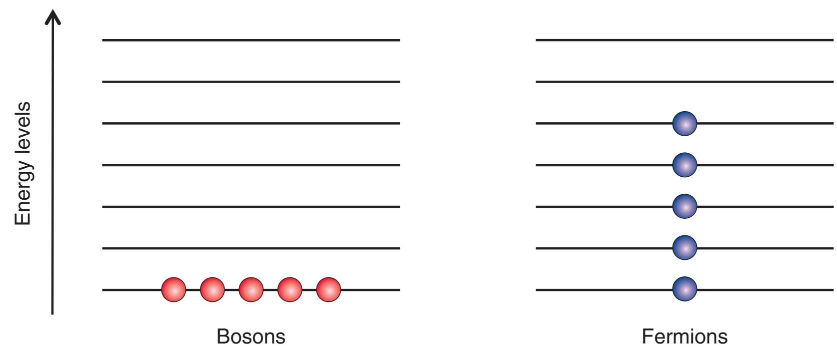


Fig. 3. Two different types of quantum-mechanical particle.

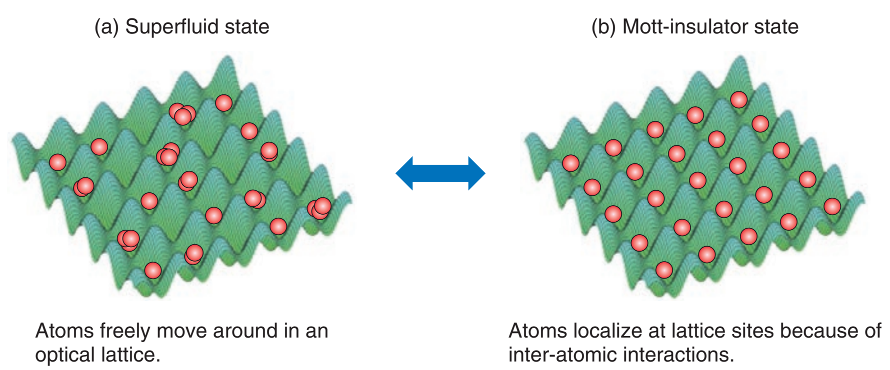


Fig. 4. Simulation of quantum phase transition from a superfluid to a Mott-insulator.

atoms. On the other hand, fermions have a completely different property from bosons: multiple fermions cannot occupy a single energy level. Typical examples of fermions are electrons, protons, and neutrons. Textbooks on condensed matter physics explain many properties of metals and semiconductors on the basis of the fermionic nature of electrons. Furthermore, superconductivity arises from the fact that fermionic electrons form an ensemble of electron pairs and each electron pair behaves as a boson.

In condensed matter physics, we generally explore the universal features of matter by studying the widest possible range of materials. Quantum simulation via ultracold atomic gases in an optical lattice provides us with a different approach: we investigate universal features directly via artificial model systems created by highly controllable atoms and laser lights that mimic materials. It should be noted here that isotopes play an important role in such quantum simulation. Most atomic species have several stable isotopes containing different numbers of neutrons inside the nucleus. For example, ytterbium has seven stable isotopes: five of them are bosons while the other two are fermions. By using this rich range of isotopes, we can freely choose bosons and/or fermions to investigate. This indicates the great advantage of quantum simulation. Even a single atomic species like ytterbium allows us to investigate various aspects of matter such as superfluids, metals, insulators, superconductors, and magnets.

4. Simulation of quantum phase transitions

Next, we briefly introduce the pioneering work done by the research group at the Max Planck Institute of Quantum Optics in Germany [4], which demonstrated quantum simulation using optical lattices for the first time.

In their experiments, bosonic atoms of rubidium (mass number: 87) were cooled to ultralow temperatures on the nanokelvin order and confined in an optical lattice. As depicted in **Fig. 4(a)**, bosonic atoms stay in the superfluid state at such a low temperature and they can move around freely over all of the lattice sites. However, this situation is limited to the case where the intensity of lattice lasers is low enough and the depth of the optical lattice potential is correspondingly shallow. When the intensity of the lattice lasers is stronger and the optical lattice potential becomes deeper, the interaction between atoms plays a significant role in the quantum states of atoms. In particular, in the case of repulsive interactions where atoms repel each other, bosonic atoms cannot move freely because of the interactions and they are finally localized at lattice sites, as shown in **Fig. 4(b)**. Such localization of bosonic atoms reflects their insulating properties. This insulator state caused by interactions is called a *Mott insulator* after its theoretical proposer, Sir Nevill Mott.

A quantum phase transition (QPT) drastically changes the characteristics of a substance. This phenomenon is caused by many quantum mechanical particles included in the substance such as electrons. QPTs are therefore one of the main research topics in condensed matter physics as a typical example of complicated many-body problems. Figure 4 indicates that, surprisingly, we can simulate the QPT from a superfluid to a Mott-insulator in condensed matter physics by means of ultracold atomic gases confined in optical lattices. Note that the Mott-insulator state is strongly related to the mechanism of high-temperature superconductivity. Similar studies using ultracold fermionic atoms have already been performed mimicking electrons in high-temperature superconductors. On the other hand, as clearly seen in Fig. 4(b), all of the atoms in the Mott-insulator state are strictly ordered in alignment with lattice sites. This sheds light on another promising application of ultracold atoms other than quantum simulation. We should be able to build a scalable quantum computer utilizing every single atom in a lattice as an ideal quantum bit.

5. Recent results: Diverse quantum states achieved in mixtures of bosons and fermions

The diverse properties of substances are closely related to the different characteristics of bosons and fermions, as mentioned above. Perhaps you wonder what kind of quantum states will be achieved by mixing these two fundamental particles—bosons and fermions—in an optical lattice. Of course, such a mixture does not exist in nature. Kyoto University and NTT worked in collaboration to elucidate this unresolved problem [3].

In this collaboration, the research group at Kyoto University performed the experimental studies. Two kinds of atomic gas consisting of bosonic and fermionic ytterbium isotopes were cooled to temperatures of a few nanokelvins and mixed in the optical lattice. All of the experiments were conducted under the condition that the optical lattice was sufficiently deep; hence, both ytterbium gases were in the Mott-insulator regime. This significantly simplified the characteristics of mixtures and made it possible to focus on the influence of interactions between bosons and fermions. The research group at NTT theoretically analyzed the experimental data measured by the Kyoto University group. We used our own calculation method, which corresponds to an extension of the Gutzwiller approximation* to finite temperatures. We precisely compared the experiments and calculations and clarified that the ytterbium isotopes form the novel quantum states in which bosons and fermions are highly entangled. These states are far from the simple Mott-insulators shown in Fig. 4.

The quantum states of boson-fermion mixtures elucidated by our research collaboration are summarized in **Fig. 5**. We have studied two cases classified by whether the interaction between bosons and fermions is repulsive or attractive. First, when the interaction is repulsive and the numbers of both particle types are comparable, bosons and fermions repel each other and mix randomly, leading to a random arrangement of single bosons and single fermions at the optical lattice sites, as shown in Fig. 5(a). This state is a completely new quantum state of matter that has been confirmed for the first time in the world; it is referred to as a *mixed Mott-insulator*. However, when the number of fermions greatly exceeds the number of bosons, both particles are distributed among the optical lattice sites in a spatially separated manner, as shown in Fig. 5(b). We can understand that such a quantum state (i.e., phase separated state) reflects the difference between bosons and fermions depicted in Fig. 3. Bosons tend to occupy lattice sites with multiple bosons at each site, while fermions tend to exhibit single occupancy.

Next, when the interaction between bosons and fermions is attractive, the quantum states of the mixtures are completely different to those in the

* The Gutzwiller approximation is an important theoretical method of approximate calculations in condensed matter physics formulated by Martin C. Gutzwiller. This method enables us to efficiently calculate the effects of atomic interactions in an optical lattice.

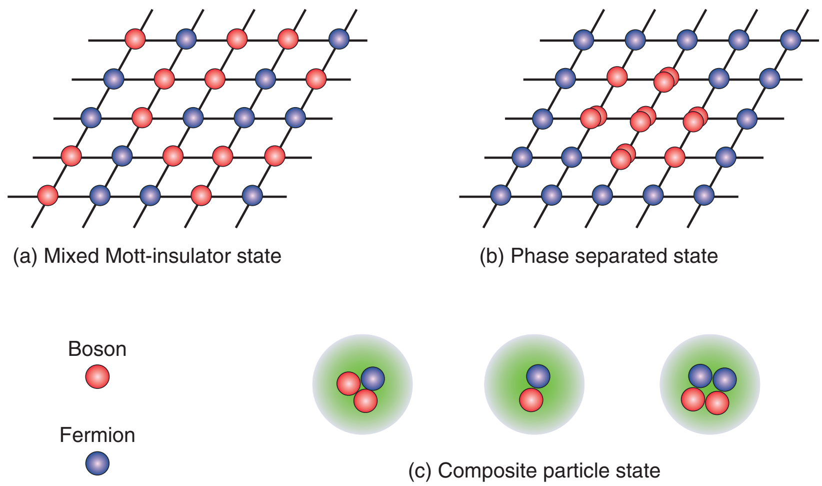


Fig. 5. Diverse quantum states observed in mixtures of bosons and fermions.

above-mentioned case of repulsive interaction. We have revealed that multiple bosons and fermions combine at lattice sites and form composite particle states, as shown in Fig. 5(c). Interestingly, this composite particle state has different components depending on the numbers of bosons and fermions included in the mixture.

In summary, we have observed diverse quantum states in mixtures of bosons and fermions confined in an optical lattice as a result of the interplay between the characteristics and the interactions of these two different fundamental particles. These quantum simulation results provide us with the important basic concept for one possible origin of diverse phenomena that we generally find in condensed matter systems.

6. Future prospects

Quantum simulation by means of ultracold atomic gases in optical lattices has been making rapid progress in recent years, involving various research fields such as condensed matter physics, quantum information, and quantum chemistry. We are sure that a wide range of research activities seeking both basic studies and future applications is now very important. NTT Basic Research Laboratories is developing quantum technologies for ultracold atomic gases through close mutual cooperation between theoretical and experimental studies. The final aim is to construct a quantum computer based on an optical lattice utilizing single atoms as quantum bits.

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Makoto Yamashita
Senior Research Scientist, Optical Science Laboratory, Quantum Optical State Control Research Group, NTT Basic Research Laboratories.

He received the B.E., M.E., and Dr.Eng. degrees in applied physics from Osaka University in 1987, 1989, and 1992, respectively. Since joining NTT Basic Research Laboratories in 1992, he has been experimentally studying quantum noise in semiconductor lasers and theoretically studying the quantum dynamics of ultracold atoms. His current research interests are quantum phase transitions and quantum dynamics of ultracold atoms in optical lattices. Since 2008, he has been collaborating with Professor Yoshiro Takahashi at Kyoto University as a member of the CREST project of the Japan Science and Technology Agency (JST). He is a member of the Physical Society of Japan (JPS), the Japan Society of Applied Physics, and the American Physical Society.

Kensuke Inaba
Optical Science Laboratory, Quantum Optical State Control Research Group, NTT Basic Research Laboratories.

He received the B.E., M.E., and Dr.Eng. degrees from the Department of Applied Physics, Osaka University, in 2003, 2005, and 2007, respectively. He joined NTT Basic Research Laboratories in 2008. Since 2004, he has been studying quantum many-body physics in correlated electron systems in condensed matter. His current interests are correlated cold atoms and their application to a quantum simulator. Since 2008, he has been collaborating with Professor Yoshiro Takahashi at Kyoto University as a member of the CREST project of JST. He is a member of JPS.

Method of Handling Hard Disk Drive Failures in Cloud Computing Environment

Jin Hiwatashi and Sotetsu Iwamura

Abstract

In this article, we present a method of handling failures of hard disk drives (HDDs) in a cloud computing environment deployed for research and development purposes. We identified two problems associated with HDD failures: (1) how to ascertain the failure frequency of each HDD and (2) how to ascertain the lifetime of a specific HDD. For the first problem, we devised a method for estimating the necessary number of replacement HDDs by using an HDD lifetime distribution. For the second problem, we devised a method for estimating the remaining life of an HDD by using HDD failure physics and replacing all HDDs on a preventative basis during regular maintenance.

1. Introduction

NTT Software Innovation Center is researching and developing an R&D (research and development) cloud in order to establish technologies for developing cloud computing services. Because this R&D cloud consists of a large number of diverse devices, one important issue for its operation is how to handle frequent device failures. This issue can be divided into two main problems.

The first problem is how to ascertain the failure frequency of each type of device. Failed devices are usually replaced during maintenance. To ensure that enough replacement devices are kept on hand, it is necessary to forecast the number of device failures in a given time period by considering the failure frequency of each type of device. To solve this problem, a failure rate model that uses a statistical lifetime distribution*1 independent of the target device is effective.

The second problem is how to ascertain the lifetime of a specific device. Devices expected to fail are usually identified and replaced as a preventative measure during regular maintenance. Determining the likelihood of failure requires forecasting the lifetime of each device. While it is possible to apply the failure rate model with a statistical lifetime distribution as described above for this problem, its forecasting accuracy is low, a few percent at best, so it cannot be used without modification. To solve this problem, a failure rate model with improved forecasting accuracy achieved through active use of knowledge (failure physics*2) about the particular device is effective.

In this article, we report examining hard disk drives (HDDs), which fail relatively frequently, and developing an HDD failure rate model for a cloud computing environment used to implement an R&D cloud. We analyzed the past failure statistics of an HDD cluster that had a particularly high rate of HDD failures in the R&D cloud and devised two methods of estimating HDD failure rates (Sections 2 and 3, respectively). Section 2 describes the application of a failure rate model using statistical lifetime distributions for HDD failures. As a specific application of this model, we present a method for estimating the number of HDDs required over a specific time period in order to have a sufficient number of replacement HDDs on hand. Section 3 describes the application of a failure rate model using failure physics for HDD failures. As a specific application of this model, we

*1 Lifetime distribution: A distribution that follows the time until an item fails.

*2 Failure physics: Research into failures from the perspective of the physical and chemical processes that lead to failure or damage.

present a method for discovering HDDs likely to fail and replacing them preventatively during regular maintenance. Finally, Section 4 concludes with a summary.

2. Method for ascertaining HDD failure frequencies

Replacement HDDs were stockpiled prior to the startup of the R&D cloud's high-failure-rate cluster (Cluster A). The number intended to be sufficient for a year was calculated assuming, on the basis of existing research [1], [2], the annual failure rate*3 to be 3%. After Cluster A went into operation, however, HDD failures began occurring at an annual failure rate of over 10% and the stock of replacement HDDs was exhausted in three months. From this experience, we established a method of estimating the necessary number of replacement HDDs by applying a failure model based on a statistical lifetime distribution for HDD failures.

Before constructing a failure rate model based on a lifetime distribution, it is necessary to investigate which distribution model the lifetime distribution adheres to. In the following sections, we find the lifetime distribution from past failure statistics of HDDs in Cluster A and attempt to fit three lifetime distribution models. Finally, we evaluate the three lifetime distributions to determine which has the best fit to the lifetime distribution.

2.1 Determining past failure statistics

A log was kept noting the time and date of each HDD replacement. The failure statistics are summarized in **Table 1**. The HDD lifetime distribution in **Fig. 1** was derived from the failure statistics given in Table 1. The horizontal axis in Fig. 1 represents the number of days elapsed from the reference date and the vertical axis represents the reliability of the HDDs in use on the reference date. The sudden drop in reliability at around the 120-day mark is explained by the discovery and replacement of failed or malfunctioning

Table 1. Summary of failure statistics.

Target	Cluster A
Period	January 1 to October 4, 2010
No. of servers	285
No. of HDDs	1140 (112 failed)
HDD specifications	SATA 1 TB (consumer-grade devices)

SATA: serial AT attachment (AT derives from IBM PC/AT personal computers)

*3 Annual failure rate: The percentage of devices that will fail over a period of one year out of the total number of devices.

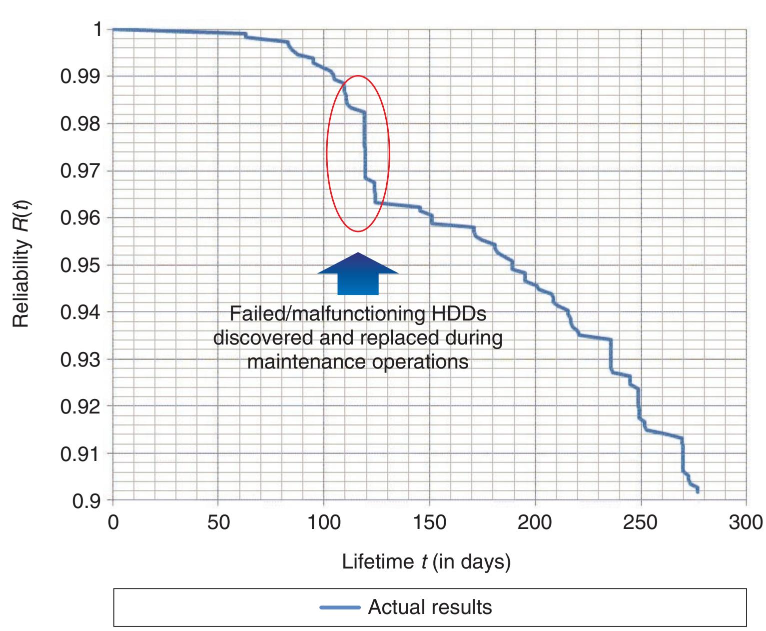

Fig. 1. HDD reliability calculated from failure statistics.

HDDs during maintenance conducted between April 30 and May 6, 2010.

2.2 Fitting past failure statistics to lifetime distribution models

Next, we selected three lifetime distribution models—exponential distribution, Weibull distribution, and log-normal distribution—as candidates for fitting the past failure statistics shown in Fig. 1.

The exponential distribution expresses the reliability $R(t)$ with Equation 1, where the failure rate $\lambda(t)$ is constant.

$$R(t)=\exp(-\lambda_0 \bullet t) \qquad (1)$$

The Weibull distribution expresses the reliability $R(t)$ with Equation 2, where the failure rate varies according to shape parameter α and scale parameter β.

$$R(t)=\exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \quad (\alpha > 0, \beta > 0) \qquad (2)$$

The log-normal distribution expresses the reliability $R(t)$ and failure rate $\lambda(t)$ with Equation 3, where the log of lifetime t follows a normal distribution.

$$R(t)=\Phi\left(\frac{\mu_{Le}-\ln t}{\sigma_{Le}}\right)$$

$$\text{where } \Phi(u)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{u}\exp\left(-\frac{u^2}{2}\right)du \qquad (3)$$

We estimated parameters to fit the failure statistics in Fig. 1 to these three distribution models. The results are listed in **Table 2**, and the values predicted using the lifetime distribution models are given in **Fig. 2**.

2.3 Evaluating the goodness of fit

It is not possible to tell from Fig. 2 which of the three models is the best fit. Therefore, we used the

Table 2. Estimated parameters and AIC results for lifetime distribution models.

Lifetime distribution	Estimated parameters	AIC
Exponential distribution	λ_0 = 0.0003	–475.9
Weibull distribution	α = 1.508, β = 1315	–591.7
Log-normal distribution	μ_{Le} = 7.433, σ_{Le} = 1.301	–567.0

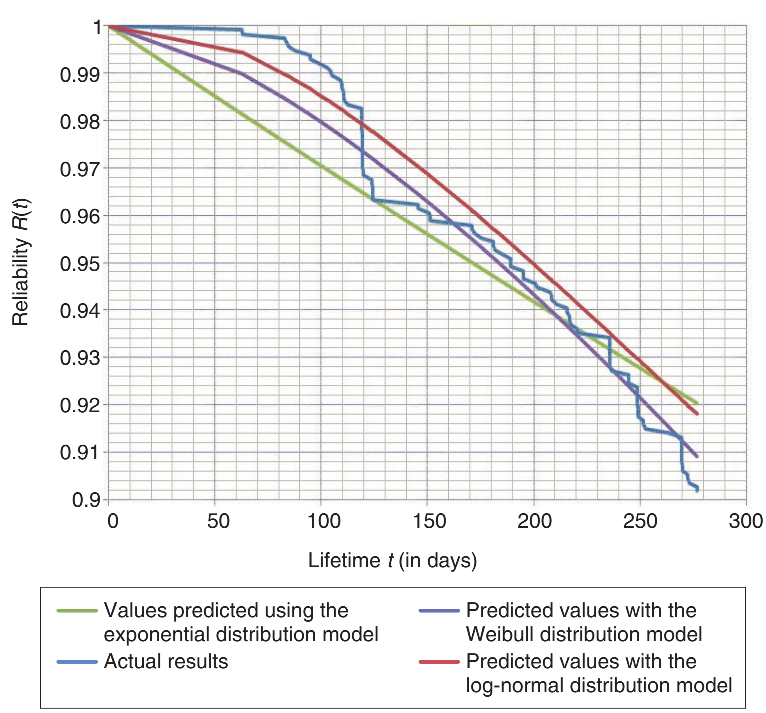

Fig. 2. HDD reliability calculated with lifetime distribution models.

Akaike information criterion (AIC)*4, a measure developed by Hirotsugu Akaike, to evaluate each model's goodness of fit. The AIC value for each model was found using Equation 4.

$$AIC = n \times \left\{ 1n\left(2\pi \frac{S_e}{n}\right) + 1 \right\} + 2(p+2) \qquad (4)$$

In this equation, n is the number of samples, S_e is the residual sum of squares, and p is the number of predictor variables. For the exponential distribution model, $p = 1$ was used, whereas for the Weibull distribution and log-normal distribution models, $p = 2$ was used. The AIC results for the lifetime distribution models are also listed in Table 2. We can see that the Weibull distribution is the best fit for the past failure statistics and the log-normal distribution is the next best fit. This result is also consistent with existing research [2]. Therefore, it is reasonable to fit the Weibull distribution to the HDD lifetime distribution.

*4 Akaike information criterion (AIC): An indicator of the relative goodness of a statistical model. It judges models using a balance between the complexity of the model (number of parameters) and the model's goodness of fit by using real data.

2.4 Method for estimating the necessary number of replacement HDDs

As a final step, we devised a method for estimating the necessary number of replacement HDDs. To do this, we first estimated the parameters of the failure rate model (Weibull distribution) for each HDD product using failure statistics over the most recent six-month to one-year period. For example, it is possible, using the failure rate model (Weibull distribution) shown in **Fig. 3**, to estimate the number of failures over a certain period by multiplying the total number of HDDs by the difference in reliabilities between the start date (day 100) and the final date (day 200). The necessary number of replacement HDDs can be easily worked out from the number of failures.

3. Method for ascertaining HDD lifetimes

The R&D cloud requires maintenance each time an HDD fails in order to replace or repair the HDD. User convenience can be improved if HDDs with little remaining life can be discovered and replaced pre-

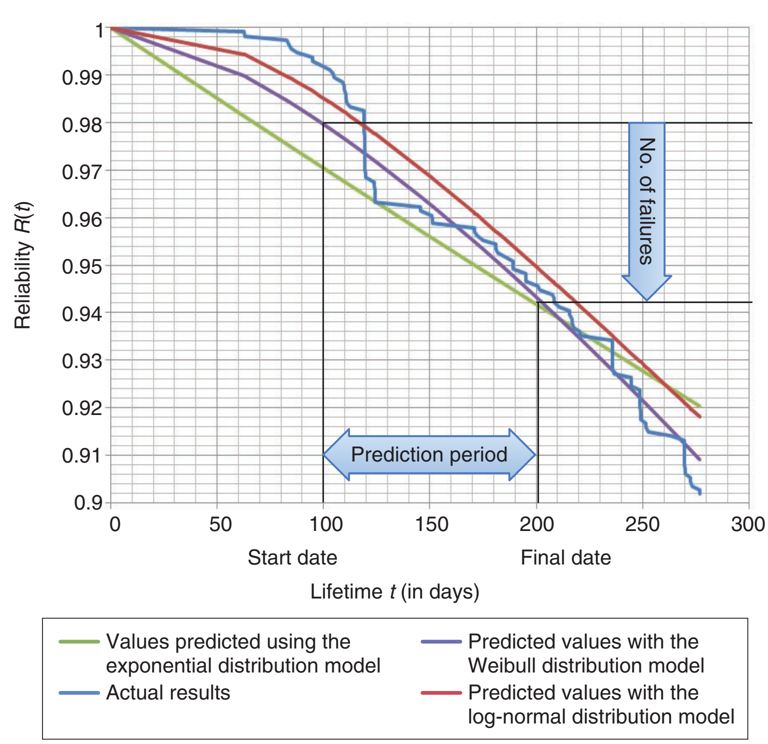

Fig. 3. Estimation of the necessary number of replacement HDDs.

ventatively during regular maintenance. Since the forecasting accuracy of failure rate models based on lifetime distributions is too low, as mentioned in Section 1, we applied a failure rate model that uses failure physics to improve the forecasting accuracy for HDD failures.

3.1 Fitting results to a rate process model

The rate process model is widely used in accelerated tests for electronic components including HDDs. It expresses the lifetime t with Equation 5. Therefore, we continue the argument in this article on the assumption that HDD failure physics conforms to the rate process model.

$$t = BS^{-n} \cdot \exp\left(\frac{U}{kT}\right) \quad (5)$$

In this equation, S is the load (physical stresses and voltage), U is the activation energy, k is Boltzmann's constant, T is the absolute temperature, and B and n are constants.

The absolute temperature can be considered to be constant since the R&D cloud's computing environment is climate controlled to ensure uniform temperature and humidity levels. Assuming constant temperature means that $B \cdot exp(U/kT)$ is also constant because U, k, and B are constants. Replacing this constant in Equation 5 with C gives Equation 6.

$$t = CS^{-n} \quad (6)$$

Taking the log on both sides of Equation 6 gives Equation 7.

$$\ln t = -n \cdot \ln S + \ln C \quad (7)$$

Equation 7 can be applied as a failure rate model (lifetime model) based on HDD failure physics under fixed temperature conditions. However, it is necessary to estimate parameters C and n for each HDD product in order to forecast the lifetime t by using Equation 7's failure rate model.

Estimating C and n requires measuring the load S (physical stresses and voltage) applied to the HDD and the resulting lifetime t. Because of the difficulty in making these measurements, we made the following two assumptions for the purposes of this article.

3.1.1 Assumptions about load *S*

The load S (physical stresses and voltage) applied to an HDD consists of vibrations and impacts (physical stresses) and excess voltages. For example, applying vibrations or impacts to an HDD will cause media scratches and media failures. If spare sectors are assignable, the RAID (redundant array of independent disks) card will record the number of media failures, but if spare sectors are not available, the HDD will fail. Thus, applying load may cause a failure. If recovery from the failure is possible, this is recorded in the HDD information, but if not, the HDD will fail.

Since the load can be approximated from HDD information that is measureable via the RAID controller, we assumed a linear relationship exists between the load and some HDD information.

3.1.2 Assumptions about lifetime *t*

While it is possible to measure the lifetime t of an HDD to which a load S has been applied once all HDDs in a cluster have failed, lifetime estimation is meaningless at this point. Instead, we collected HDDs where the applied load fell in a certain region using statistical techniques and assumed that the average lifetime μ found from the reliability $R(t)$ of HDDs in the collection is equivalent to the lifetime t [3].

The average lifetime μ is expressed with Equation 8 in the failure rate model (Weibull distribution) described in Section 2. Furthermore, α can be assumed to be constant within the range of ordinary usage, although α does change when larger loads are applied.

$$\mu = \beta \cdot \Gamma\left(\frac{1}{\alpha}+1\right) \quad (8)$$

3.2 Examining the correlation between HDD information and average lifetimes

With the above two assumptions, it is possible to estimate parameters C and n from the correlation between HDD information and average lifetimes. In this section, we provide an example of estimating them for Cluster A, as used before in Section 2.

3.2.1 Measuring HDD information

The measurement conditions and parameters used to measure HDD information are given in **Tables 3** and **4**, respectively. After measuring the HDD information, we found the frequency distribution of HDDs where HDD information values fell in certain segments (i.e., the number of HDDs) and the frequency distribution of failed HDDs in each segment (i.e., the number of failures). The segments selected were 0 to 1 and 2^{n-1} to $2^n - 1$ (where n is an integer larger than 1). The segments were selected using the knowledge that the equations are logarithmic.

From the number of HDDs and the number of failures, we found the reliability $R(t)$ in each segment

Table 3. HDD information measurement conditions.

Targeted cluster	Cluster A
Targeted HDDs	HDDs operating on the reference date (1140 devices in total, 83 failed devices)
Measurement date	September 1, 2010
Measurement values	Directly recorded values for each measurement parameter (see Table 4)

Table 4. HDD information measurement parameters.

Parameter	Description
Aborted commands	Number of times commands issued by the RAID controller were aborted
Media failures	Number of times spare sectors were assigned because of HDD media failures
Connection failures	Number of times the RAID controller failed to connect to the HDD
Parity errors	Number of parity errors
Hardware errors	Number of hardware errors
S.M.A.R.T. warnings	Number of S.M.A.R.T. parameter warnings

S.M.A.R.T: self-monitoring, analysis, and reporting technology

and found β with Equation 2 and the average lifetime μ with Equation 8. Because α was assumed to be constant, the value found in Section 2 (α= 1.508) was applied.

3.2.2 Identifying HDD information needed for correlation with average lifetime

Using the method described above, we found a correlation between HDD information and the average lifetime. Of the HDD information measurement parameters in Table 4, some degree of correlation was found for the number of aborted commands, the number of media failures, and the number of connection failures. Parameters C and n were estimated using this correlation.

The correlation between aborted commands $A.C.$ and average lifetime μ is shown in **Fig. 4**. We performed a linear regression analysis with the expectation of a negative linear relationship between the logarithm of aborted commands and the logarithm of average lifetime. Equation 9 was obtained as an approximation curve.

$$\ln \mu = -0.1410 \times \ln A.C. + 7.169 \quad (9)$$

Note that the Pearson product-moment correlation coefficient is R = -0.7555.

The correlation between media failures $M.E.$ and average lifetime μ is shown in **Fig. 5**. We performed a linear regression analysis again, and Equation 10 was obtained as an approximation curve.

$$\ln \mu = -0.6649 \times \ln M.E. + 6.744 \quad (10)$$

Note that the Pearson product-moment correlation coefficient in this case is R = -0.9616.

The correlation between connection failures $L.F.$ and average lifetime is shown in **Fig. 6**. We performed a linear regression analysis again, and Equation 11 was obtained as an approximation curve.

$$\ln \mu = -0.2776 \times \ln L.F. + 6.535 \quad (11)$$

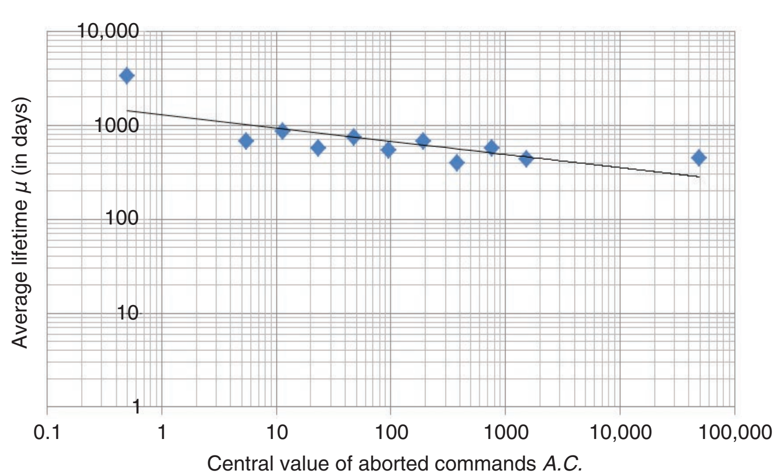

Fig. 4. Correlation between aborted commands and the average lifetime.

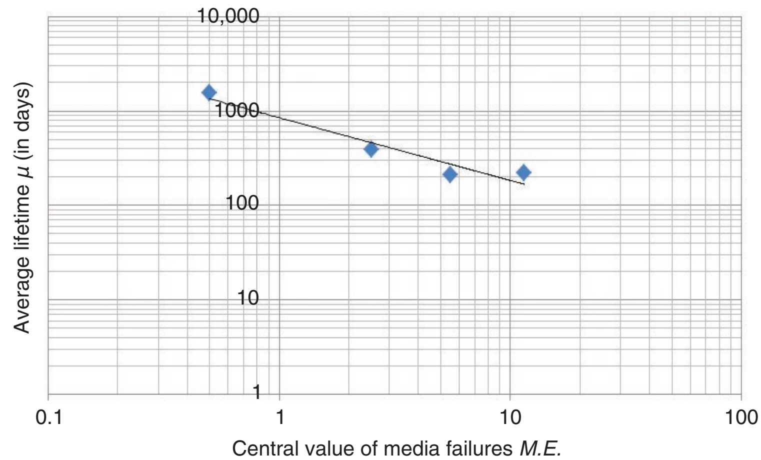

Fig. 5. Correlation between media failures and average lifetime.

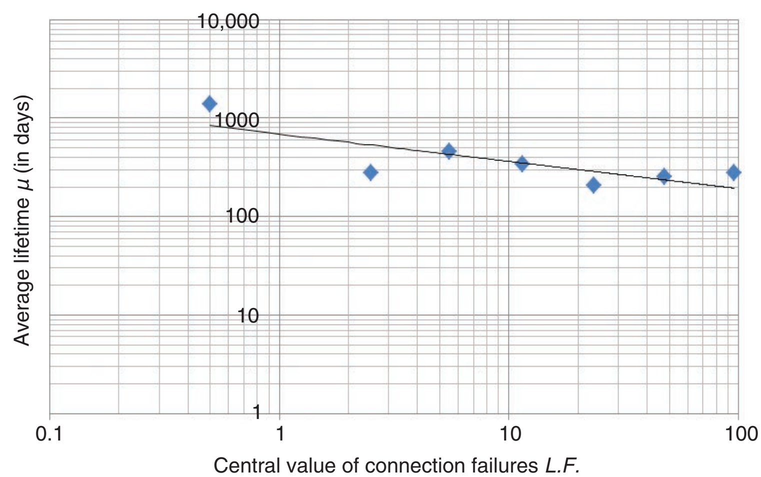

Fig. 6. Correlation between connection failures and average lifetime.

3.2.3 Validating the correlations

From Figs. 4, 5, and 6, it is not possible to determine whether the correlations are statistically significant. Therefore, we examined the correlations with a significance test using Pearson product-moment correlation coefficients. The test statistic t_0 in the significance test is expressed by Equation 12.

$$t_0 = \frac{|R|\sqrt{n-2}}{\sqrt{1-R^2}} \tag{12}$$

Here, n is the sample size (number of data points) and R is the sample correlation coefficient. Because t_0 follows the t distribution with $n - 2$ degrees of freedom, the significance level P was found to be $P=\Pr\{|t| \geq t_0\}$. The results are listed in **Table 5**. With the acceptable level of significance set to 5% ($P \leq 0.05$), the numbers of aborted commands, media failures, and connection failures were recognized as having statistically significant correlations with the average lifetime.

3.3 Method for estimating HDD lifetimes

Finally, we describe a method for estimating HDD lifetimes. First, we ascertained the past failure statistics of the targeted cluster and examined the correlation between HDD information and average lifetime. When given a specific HDD, the method measures

Table 5. Values of variables in significance test.

Tested factor	Sample size n	Correlation coefficient R	Test statistic t_0	Significance level P
Aborted commands	11	–0.7555	3.460	0.03837
Media failures	4	–0.9616	4.957	0.007162
Connection failures	7	–0.7879	2.861	0.03538

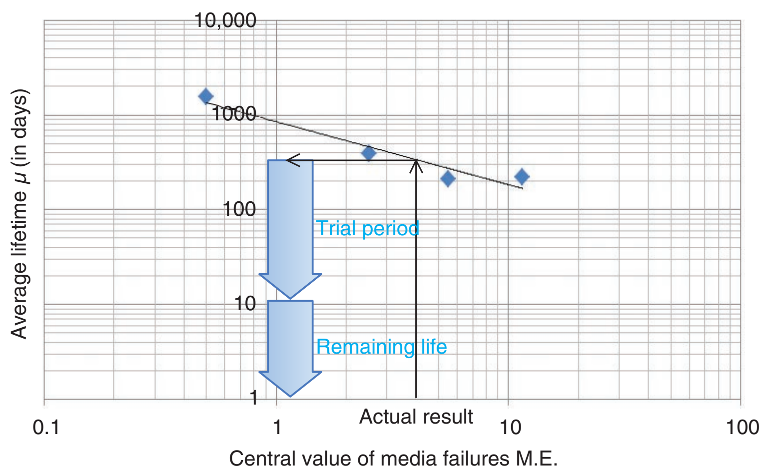

Fig. 7. Estimation of remaining life of an HDD.

the HDD's information, fits the information to known correlations, and estimates the average lifetime. The remaining life can be calculated by subtracting the time in use to date. If an HDD has a short remaining life, it is replaced with a new one.

For example, the lifetime of an HDD with four media failures (measured value) is estimated using Equation 10 to be 338 days, given the correlation between media failures and average lifetime shown in **Fig. 7**. If the HDD had been in use for 328 days at the time of the measurement, it would be replaced with a new HDD since its remaining life would be only 10 days.

The R&D cloud is managed and operated through a system that displays resources such as power consumption. We plan to integrate this method with the resource visualization system, as illustrated in **Fig. 8**, in the future to let cloud operators ascertain the remaining lives of HDDs at a glance.

4. Conclusion

In this article we described a method of handling HDD failures that occur frequently in the operation of an R&D cloud. In Section 1, we indicated two problems associated with HDD failures: how to ascertain the failure frequency of each HDD and how to ascertain the lifetime of a specific HDD.

In Section 2, we described an approach to the first problem. We began by examining the past HDD failure statistics of a high-failure-rate cluster (Cluster A). We found the HDD lifetime distribution from the failure statistics and fitted them to three lifetime distribution models. Using the Akaike information criterion, we demonstrated that the Weibull distribution (with shape parameter α of 1.508) was the best fit for the HDD lifetime distribution. We then applied this finding in a method for estimating the necessary number of replacement HDDs.

In Section 3, we described an approach to the second problem. We began by assuming that HDD failure physics follows the rate process model and examined the correlation between information about HDD output by RAID controllers and the average lifetime in Cluster A, which was also used in Section 2. We described how a statistically significant correlation was recognized between specific HDD information (numbers of aborted commands, media failures, and

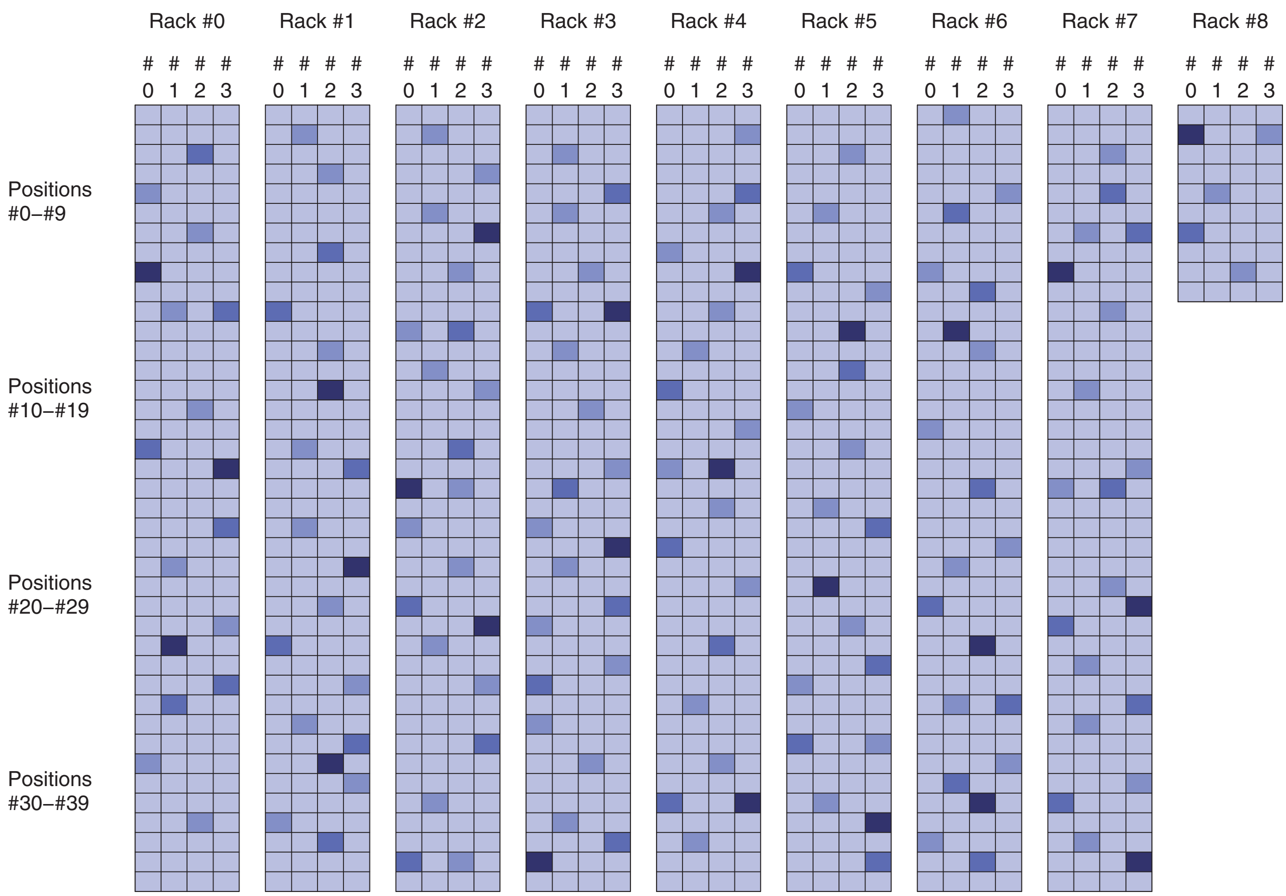

Fig. 8. Conceptual image of integration with visualization system.

connection failures) and the average lifetime using a significance test with Pearson product-moment correlation coefficients. We then applied this finding in a method for estimating the remaining life of HDDs so that HDDs with short remaining lives can be replaced on a preventative basis during regular maintenance. We also described the concept of integrating this work with resource visualization systems.

The results of this research will enable us to reduce the operations for preparing replacement HDDs and those for replacing HDDs when HDD failures occur. Consequently, the operation of large-scale cloud computing environments, such as an R&D cloud, will become even more efficient.

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Jin Hiwatashi

Senior Research Engineer, Platform Technology SE Project, NTT Software Innovation Center.

He received the B.S. and M.S. degrees in electrical engineering from Waseda University, Tokyo, in 1993 and 1995, respectively. He joined NTT Network Information Systems Laboratories in Yokosuka in 1995. As a result of organizational changes in April 2012, he is now in NTT Software Innovation Center. He is a member of the Information Processing Society of Japan (IPSJ).

Sotetsu Iwamura

Senior Research Engineer, Supervisor, Platform Technology SE Project, NTT Software Innovation Center.

He received the B.S. and M.S. degrees along with the Ph.D. degree in electronic engineering from the University of Tokyo in 1989, 1991, and 1994, respectively. He joined NTT Telecommunication Networks Laboratories in Musashino in 1994. As a result of organizational changes in April 2012, he is now in NTT Software Innovation Center. He is a member of IPSJ.

Establishment of New ITU-T Focus Group Related to Disaster Relief

Hideo Imanaka and Noriyuki Araki

Abstract

At the last meeting of the Telecommunication Standardization Advisory Group (TSAG) of ITU-T (International Telecommunication Union, Telecommunication Standardization Sector) in January 2012, it was agreed that three focus groups studying new standardization areas for a limited period would be newly established in January 2012. This article provides a little background information about their establishment and touches on their study directions, especially for the focus group dealing with disaster relief. In addition, this article also introduces the main results of the TSAG meeting.

1. Overview of ITU-T TSAG meeting

ITU-T TSAG (International Telecommunication Union, Telecommunication Standardization Sector, Telecommunication Standardization Advisory Group) discusses strategic plans and working methods related to ITU-T standardization, unlike a Study Group (SG) whose role is to make Recommendations. Dr. Hideo Imanaka of NTT's R&D Planning Department, one of the authors of this article, regularly participates in TSAG meetings. TSAG discusses the SG structure of ITU-T for the next period, working methods for subjects that overlap two or more SGs, and the establishment of Focus Groups (FGs), which undertake intensive study of new standards.

As shown in **Table 1**, the TSAG meeting in January 2012 established three new FGs and two Joint Coordination Activities (JCAs). The FGs are related to disaster relief, service aspects of machine-to-machine (M2M) communication, and ways to bridge the standards gap for developing countries; the JCAs will work on a structure for making ITU-T Recommendations based on the deliverables of two FGs that concluded their work last December, namely FG Smart on the Smart Grid and FG Cloud on cloud computing.

2. Establishment of FG on disaster relief

2.1 Background

The Great East Japan Earthquake and the accompanying tsunami devastated a large part of the east coast of Japan on March 11 2011. At the subsequent annual CTO (Chief Technical Officer) meeting, which provides an opportunity for discussion of future ITU-T study subjects by CTO-level personnel from ITU-T member companies throughout the world, Japanese companies including NTT addressed the importance of standardization studies in relation to safety confirmation systems, emergency communication, and information and communications technology (ICT) systems to be utilized during a disaster [1].

The experience of Japanese telecommunications companies is expected to be useful for telecommunications operators worldwide because they faced huge damage as a result of the earthquake, tsunami, and nuclear power plant accident. In addition, Japanese telecommunications operators have a lot of experience regarding network resiliency to both earthquakes and typhoons, and this experience is going to be put to use after the flooding in Thailand in November 2011. At TSAG, the Japanese government led the discussion on establishing an FG on disaster relief as requested by the ITU-T director, and it was agreed to establish a new FG in TSAG.

The new FG covers (1) disaster relief systems, which provide relief by using ICT in the event of a disaster, (2) network resiliency, which provides sustainable communication even during a disaster, and (3) network recovery, which restores network facilities. Therefore, the new FG was named "Focus Group on Disaster Relief systems, Network Resilience

Table 1. Major results of TSAG meeting in January 2012.

Status	Former FG	New organization	Chair	Description
New		FG DR&NRR	NTT (Japan)	Disaster relief
New		FG M2M	CATR (China)	e-Health (initial target)
New		FG Innovation	NSN (Germany)	Gap analysis
Complete	FG Smart	JCA-SG&HN	Lantiq (Germany)	Expansion of JCA-HN
Complete	FG Cloud	JCA-Cloud	CISCO (USA)	New WP in SG13

WP: Working Party

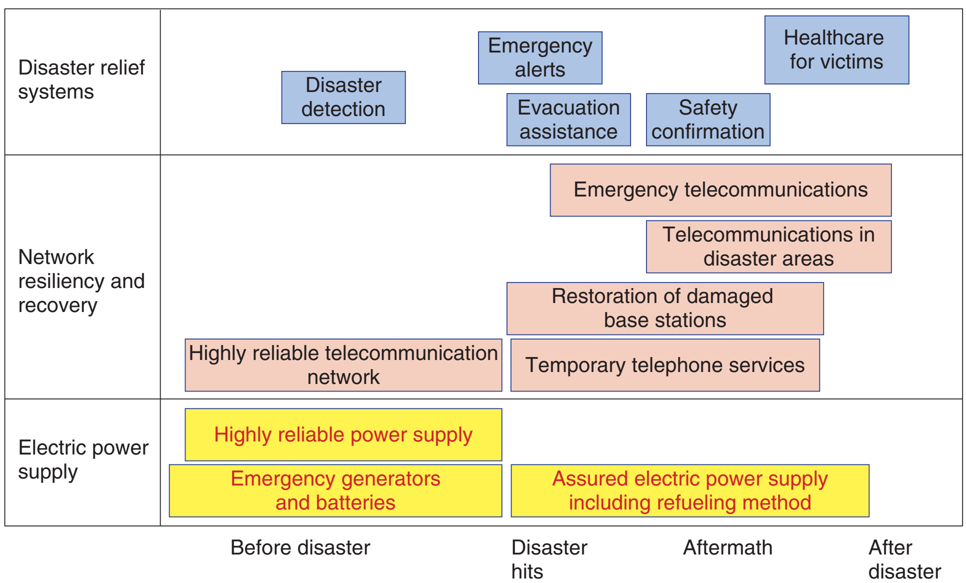

Fig. 1. Expected study scope of FG-DR&NRR.

and Recovery (FG DR&NRR)" [2].

2.2 Objectives of FG DR&NRR

The expected study area of this FG is very wide. Some examples of study items are shown in **Fig. 1**. First, we must find a way of guaranteeing a highly reliable electric power supply, for example, by using multiple electrical distribution routes and redundant electrical generation systems. We must also find a way to ensure that electric power, including a method of refueling generators, is available in the event of a disaster. Next, we must consider the subjects of network resiliency and recovery by both developing a highly reliable network design such as multiple network routes and ensuring that emergency telecommunications is available by establishing temporary telephone services when a disaster occurs and restoring damaged mobile base stations as soon as possible afterward. As regards disaster relief systems, we must study emergency warning systems, systems to assist evacuation by using digital signage, and safety confirmation systems that use the World Wide Web and voice messages. In addition, we need to consider a healthcare system for disaster victims who are living in shelters as a disaster relief system that can help ease mental stress. The FG may not cover all of these subjects, but its study area must nevertheless be very wide ranging.

In this FG, the goal is to specify disaster categories and use cases for disaster relief, describe the requirements for tackling disasters, and provide an analysis of the gap between standardization activities and subjects requiring standardization.

2.3 Plans for FG-DR&NRR

The chairman of this FG is Noriyuki Araki, the other author of this article, because Japan was deeply involved in the establishment of this FG at TSAG meetings, and NTT has a sense of responsibility that motivates it to contribute to society.

The first meeting of this FG was held in Geneva during the last week of June 2012. Following the first meeting, it is planned to hold an FG meeting once every few months. If at all possible, the meeting should be held in countries that have experienced a huge disaster in recent years, such as Indonesia, Thailand, Turkey, and Chile.

3. Overview of other FGs and JCAs

3.1 FG M2M

It was agreed to establish an FG on the service layer of machine-to-machine communication. This group is called FG M2M, as shown in Table 1. At first, it seemed that it might be difficult to obtain agreement to establish this FG because the difference between M2M and the "Internet of Things" (IoT), which is already being studied in ITU-T's IoT-GSI (GSI: Global Standards Initiative), is unclear and because it is related to "oneM2M", whose establishment is being planned by several regional standardization bodies such as the European Telecommunication Standards Institute (ETSI). Finally, after consideration of the close connection between ITU and the World Health Organization (WHO), the establishment of the FG was agreed and the first target was determined to be e-Health as an M2M application.

The chairman of FG M2M comes from the China Academy of Telecommunication Research (CATR). The first meeting was held in Geneva in April 2012 and the second meeting was held in Beijing in June 2012. In the last week of April 2012, a joint WHO-ITU workshop on e-Health was convened, and it discussed the need for e-Health standardization.

3.2 FG Innovation

To undertake a gap analysis of telecommunication standards by analyzing the best practices of ICT innovation, it was agreed to establish an FG on innovation, called FG Innovation, on the basis of a German proposal. The chairman of this FG is from a German company. This FG will discuss how to deploy standardized technologies in developing countries.

3.3 JCA-SG&HN

An FG on smart grids, called FG Smart, studied standardization of the Smart Grid from 2010, and its work was completed in December 2011. In this TSAG, it was agreed to establish JCA-Smart Grid and Home Network (JCA-SG&HN), which will coordinate standardization activities within ITU and with other standards development organizations (SDOs) to make ITU-T Recommendations based on the FG deliverables. This JCA is the former JCA-HN, which coordinated home network standardization work, and the smart grid issue is included in it because of the close relationship between these subjects.

3.4 JCA-Cloud

An FG on cloud computing, called FG Cloud, completed its work in December 2010. It was agreed to establish JCA-Cloud, which will coordinate standardization activities within ITU and with other SDOs to make ITU-T Recommendations based on the FG deliverables. It was also agreed to establish a working party, which is a study organization within an SG that handles several Questions, in SG13: the Study Group that covers future networks.

4. Future work plan

The newly established FG DR&NRR will not only study the standardization necessary to achieve networks that are robust in the event of disasters, but also play the role of distributing effective ways of proceeding during a disaster anywhere in the world based on the experiences of Japanese companies, including the NTT Group, with a view to contributing to society. NTT has been affected by many disasters such as the Great East Japan Earthquake, the Hanshin-Awaji Earthquake, many huge typhoons, and the volcanic eruption of Mt. Unzen. We believe that passing on what we have learned from these experiences to the world will repay, in some small way, the many countries that provided great help and huge support after our recent disaster.

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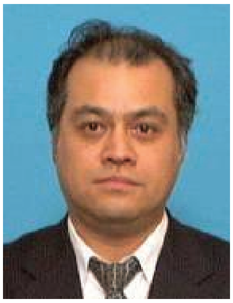

Hideo Imanaka
Senior Manager, NTT R&D Planning Department.

He received the B.E., M.E., and Ph.D. degrees in electrical engineering from Mie University in 1985, 1987, and 2001, respectively. After joining NTT Telecommunication Network Laboratories in 1987, he was engaged in research on a fiber optic access network architecture and network operation process reengineering methods. From 1996 to 2003, he worked on enterprise resource planning (ERP) systems integration as a consultant in the Solutions Business Division of NTT Communications. Since 2004, he has been involved in NGN standardization work at ITU-T. He was the Rapporteur of Question 1 of SG13 from 2007 to 2010. He has also played an active role in IPTV standardization work at ITU-T. He is currently in charge of standardization strategy in the NTT Group. He received the ITU-AJ Award from the ITU Association of Japan in 2009. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) and the Society of Instrument and Control Engineers.

Noriyuki Araki
Senior Research Engineer, Access Media Project, NTT Access Network Service Systems Laboratories.

He received the B.E. and M.E. degrees in electrical and electronic engineering from Sophia University, Tokyo, in 1993 and 1995, respectively. He joined NTT Access Network Systems Laboratories, Ibaraki, in 1995. He then worked on the R&D of operation and maintenance systems for optical fiber cable networks. Since 2006, he has been engaged in standardization work for outside plant in ITU-T SG6. He has been the Rapporteur of Question 17 of ITU-T SG15 since 2008. He has also been contributing to the activities of IEC TC86, Fibre Optics, since 2007. He is currently serving as the chairman of ITU-T FG-DR&NRR. He is a member of IEICE.

External Awards

COIN2012 IEEE ComSoc JC Young Engineer Award

Winner: Takafumi Tanaka, NTT Network Innovation Laboratories
Date: May 31, 2012
Organization: IEEE Communications Society Japan Chapter

For "Comparative Study of Optical Networks with Grid Flexibility and Traffic Grooming".

We comparatively investigated different optical network architectures characterized by grid flexibility and sub-wavelength traffic grooming. Simulation shows that the elastic models are more effective than fixed-grid models in terms of spectrum efficiency, but the trade-off between grooming gain and its additional cost should be considered, especially in elastic models.

Published as: T. Tanaka, A. Hirano, and M. Jinno, "Comparative Study of Optical Networks with Grid Flexibility and Traffic Grooming," Proc. of the 10th International Conference on Optical Internet (COIN2012), Yokohama, Japan, 2012.

ISMM 2012 Best Poster Award

Winners: Yuzuru Iwasaki, Tsutomu Horiuchi, Michiko Seyama, Toru Miura, and Emi Tamechika, NTT Microsystem Integration Laboratories
Date: June 12, 2012
Organization: 2012 The 4th International Symposium on Microchemistry and Microsystems (ISMM)

For "Quick and Simple Measurement for Antibody Array in Disposable Microfluidic Device Using Surface Plasmon Resonance".

We have developed a disposable microfluidic device that is used in conjunction with a surface plasmon resonance (SPR) instrument to perform a quick, simple immunoassay. The key technologies we have developed are a data processing method for finding the locations of active antibodies, in-situ measurement of the flow velocity, and a disposable microfluidic device with an integrated capillary pumping system. They make it possible to detect antigens in milk every 10 minutes.

2012 TTC Distinguished Service Award

Winner: THironori Ohata, NTT Cyber Solutions Laboratories
Date: June 21, 2012
Organization: The Telecommunication Technology Committee (TTC)

For achievement of standardization activity concerning multimedia systems.

2012 TTC Distinguished Service Award

Winner: Yoshiyuki Mihara, NTT Cyber Solutions Laboratories
Date: June 21, 2012
Organization: The Telecommunication Technology Committee (TTC)

For achievement of standardization activity concerning home network topology identifying protocol.

Second Place in the Hans Gros New Investigator Award Poster Presentation Competition

Winners: Dan Mikami†1, Toshitaka Kimura†1, Kouji Kadota†2, Makio Kashino†1, and Kunio Kashino†1

†1 NTT Communication Science Laboratories
†2 Osaka University

Date: July 6, 2012
Organization: 30th International Conference on Biomechanics in Sports

For "INTER-TRIAL DIFFERENCE ANALYSIS THROUGH APPEARANCE-BASED MOTION TRACKING".

The purpose of this study is to develop a method for quantitative evaluation and visualization of inter-trial differences in the motion of athletes. Previous methods for kinematic analysis of human movement have required attaching specific equipment to a body segment or can only be used in an environment designed for analyses. Therefore, they are difficult to use for observing motions in real games. To enhance the applicability to real-game situations, we propose appearance-based motion tracking. Our method only requires an image sequence from a camera. From the image sequence, automatic detection of trials and a difference analysis of them are conducted. We applied our method to the analysis of pitching motions in actual baseball games. Though we have no quantitative evaluations yet, the experimental results imply the efficacy of our method.
Published as: D. Mikami, T. Kimura, K. Kadota, M. Kashino, and K. Kasino, "INTER-TRIAL DIFFERENCE ANALYSIS THROUGH APPEARANCE-BASED MOTION TRACKING," Proc. of the 30 International Conference on Biomechanics in Sports, Melbourne, Australia, 2012.

Best Paper Award

Winners: Hiroyuki Shindo†1, Yusuke Miyao†2, Akinori Fujino†1, and Masaaki Nagata†1

†1 NTT Communication Science Laboratories
†2 National Institute of Informatics

Date: July 10, 2012
Organization: The 50th Annual Meeting of the Association for Computational Linguistics

For "Bayesian Symbol-Refined Tree Substitution Grammars for Syntactic Parsing".

Published as: H. Shindo, Y. Miyao, A. Fujino, and M. Nagata, "Bayesian Symbol-Refined Tree Substitution Grammars for Syntactic Parsing," Proc. of the 50th Annual Meeting of the Association for Computational Linguistics, pp. 440–448, Jeju, Korea, 2012.

Papers Published in Technical Journals and Conference Proceedings

Explicit beat structure modeling for non-negative matrix factorization-based multipitch analysis

K. Ochiai, H. Kameoka, and S. Sagayama

Proc. of ICASSP 2012, Vol. 1, No. 1, pp. 133–136, Kyoto, Japan.

This paper proposes model-based non-negative matrix factorization (NMF) for estimating basis spectra and activations, detecting note onsets and offsets, and determining beat locations, simultaneously. Multipitch analysis is a process of detecting the pitch and onset of each note from a musical signal. Conventional NMF-based approaches often lead to unsatisfactory results very possibly because of the lack of musically meaningful constraints. As music is highly structured in terms of the temporal regularity underlying the onset occurrences of notes, we use this rhythmic structure to constrain NMF by parametrically modeling each note activation with a Gaussian mixture and derive an algorithm for iteratively updating model parameters. It is experimentally shown that the proposed model outperforms the standard NMF algorithms as regards onset detection rate.

Comparative evaluations of various harmonic/percussive sound separation algorithms based on anisotropic continuity of spectrogram

H. Tachibana, H. Kameoka, N. Ono, and S. Sagayama

Proc. of ICASSP 2012, Vol. 1, No. 1, pp. 465–468, Kyoto, Japan.

In this paper, we explore several algorithms to find the best performing algorithm for harmonic and percussive sound separation (HPSS) based on anisotropic continuity of a spectrogram through comparative evaluation of their experimental performance. Separating harmonic and percussive sounds is useful as a preprocessor for many music analysis purposes, including chord estimation and rhythm analysis, and other music information retrieval tasks. We have introduced a method called HPSS (Harmonic/Percussive Sound Separation) that decomposes a music signal into two components by separating the spectrogram into horizontally continuous and vertically continuous components, which roughly correspond to harmonic and percussive sounds, respectively. Though there are many possible ways to achieve the HPSS algorithm on the basis of this concept, it has not been known which algorithm performs best. This paper describes five different HPSS algorithms and compares their performances for real music signals.

Constrained and regularized variants of non-negative matrix factorization incorporating music-specific constraints

H. Kameoka, M. Nakano, K. Ochiai, Y. Imoto, K. Kashino, and S. Sagayama

Proc. of ICASSP 2012, Vol. 1, No. 1, pp. 5365–5368, Kyoto, Japan.

Music spectrograms typically have many structural regularities that can be exploited to help solve the problem of decomposing a given spectrogram into distinct musically meaningful components. In this paper, we introduce new variants of the non-negative matrix factorization concept that incorporate music-specific constraints.

RoF-DAS over WDM-PON using bandpass-sampling and optical TDM techniques as universal network for broadband wireless access

K. Tsukamoto, T. Iwakuni, K. Miyamoto, T. Higashino, S. Komaki, T. Tashiro, Y. Fukada, J. Kani, N. Yoshimoto, and K. Iwatsuki

Proc. of the 31st Progress In Electromagnetics Research Symposium, Vol. 1, No. 1, pp. 491–495, KL, Malaysia, 2012.

With the explosive growth of mobile communication traffic, the air interface of mobile services has rapidly improved, and new services are being provided in new radio frequency bands. Moreover, to effectively use frequency or network resources and avoid their bottlenecks, the use of femto-cell or pico-cell architectures has been started. Backhaul networks accommodating a huge number of these pico- and femto-cell stations have become a more important issue. Broadband fixed access networks such as fiber-to-the-home (FTTH) systems will play an important role as an entrance network for broadband wireless access. Radio-over-fiber (RoF) technologies can transparently transmit various types of radio services, and their use as entrance networks achieves an effective universal platform for newly arriving air interfaces. RoF-DAS (DAS: distributed antenna system) over a wavelength-division-multiplexing passive optical network (WDM-PON) using bandpass-sampling and optical time-division-multiplexing (TDM) techniques has been proposed as a universal entrance network for broadband wireless access. This paper introduces its proposed architecture and reports the latest results of experimental and theoretical investigation of the transmission performance.

Effect of source-motion and self-motion on the resetting of auditory scene analysis

H. Kondo, D. Pressnitzer, I. Toshima, and M. Kashino

Acoustics 2012, Journal of the Acoustical Society of America, Vol. 131, No. 4, p. 3268, Hong Kong, China.

Auditory scene analysis needs to parse the incoming flow of acoustic information into perceptual streams, such as distinct musical melodies or sentences from a single talker. Previous studies have demonstrated that the formation of auditory streams is not instantaneous: rather, streaming builds up over time and can be reset by sudden changes in the acoustics of the scene. The present study examined the effect of changes induced by voluntary head motion on streaming. A telepresence robot in a virtual-reality setup was used to disentangle all potential consequences of head motion: changes in acoustic cues at the ears, changes in apparent sound location, and changes in motor processes. The results showed that self-motion induced resetting of auditory streaming. An additive model analysis further revealed that resetting was largely influenced by acoustic cues and apparent sound location rather than by non-auditory factors related to head motion. Thus, low-level changes in sensory cues can affect perceptual organization, even though those changes are fully accounted for by self-motion of the listener. These results may reflect a widely distributed neural architecture for the formation of auditory streams.

One-by-one H_2 bubble counting during water electrolysis with a chemical electrometer

N. Clement, K. Nishiguchi, J. -F. Dufreche, D. Guerin, A. Fujiwara, and D. Vuillaume

MRS Meeting, Materials Research Society, San Francisco, CA, USA, 2012.

We demonstrated the detection of hydrogen bubbles by using an ion-sensitive field-effect transistor (FET) based on a silicon transistor. Hydrogen bubbles are generated during electrolysis of an electrolyte and change the Nernst potential. Since the FET has high charge sensitivity, a small change in the Nernst potential caused by bubbles with a diameter of a few micrometers can be detected by the FET.

Layered boron nitride as a release layer for mechanical transfer of GaN-based devices

Y. Kobayashi, K. Kumakura, T. Akasaka, and T. Makimoto

Nature, Vol. 484, pp. 223–227, 2012.

Nitride semiconductors are the materials of choice for a variety of device applications, notably optoelectronics and high-frequency/high-power electronics. One important practical goal is to realize such devices on large, flexible, and affordable substrates, on which direct growth of nitride semiconductors of sufficient quality is problematic. Several techniques—such as laser lift-off—have been investigated to enable the transfer of nitride devices from one substrate to another, but existing methods still have some important disadvantages. Here we demonstrate that hexagonal boron nitride (h-BN) can form a release layer that enables the mechanical transfer of gallium nitride (GaN)-based device structures onto foreign substrates. The h-BN layer serves two purposes: it acts as a buffer layer for the growth of high-quality GaN-based semiconductors, and it provides a shear plane that makes it straightforward to release the resulting devices. We illustrate the potential versatility of this approach by using h-BN-buffered sapphire substrates to grow an AlGaN/GaN heterostructure with electron mobility of $1100\,cm^2\,V^{-1}\,s^{-1}$, an InGaN/GaN multiple-quantum-well structure, and a multiple-quantum-well light-emitting diode. These device structures, ranging in area from 5 mm × 5 mm to 2 cm × 2 cm, are then mechanically released from the sapphire substrates and successfully transferred onto other substrates.

First-principles study of nonclassical effects in silicon-based nanocapacitors

H. Kageshima and A. Fujiwara

Phys. Rev. B, Vol. 85, No. 20, 205304, 2012.

Properties of silicon-based nanocapacitors are studied from first principles. The nanocapacitor consists of electrodes of the silicon-based material planar polysilane. Nonclassical effects are analyzed by changing both the electrode spacing and the applied bias simultaneously. Even when the electrode spacing is fixed, the effective electrode spacing decreases with applied bias because of the quantum capacitance effect. In addition, when the electrostatic capacitance is analyzed in detail, it is also found that the effective electrode surface changes in a complicated manner with electrode spacing and applied bias because of the dielectric polarization effect of the electrode material. The dielectric polarization effect is one order of the magnitude smaller than the quantum capacitance effect, which is due to the nature of the electrode material, planar polysilane. It is clarified that a nanocapacitor is governed by the detailed properties of the electronic states of the electrode materials as well as the geometry.

Experimental Demonstration of Spatial Correlation Reduction Effect at MIMO Channel in RoF-DAS over WDM-PON System

T. Iwakuni, K. Miyamoto, T. Higashino, K. Tsukamoto, S. Komaki, T. Tashiro, Y. Fukada, J. Kani, N. Yoshimoto, and K. Iwatsuki

Proc. of APMP 2012, p. PA-14, Kyoto, Japan.

A radio-over-fiber distributed antenna system (RoF-DAS) over a wavelength-division-multiplexing passive optical network (WDM-PON) with multiple-input multiple-output (MIMO) has been proposed. The DAS has the effect of reducing the spatial correlation between MIMO channels. This paper describes an experimental demonstration of the spatial correlation reduction effect in an RoF-DAS system compared with a conventional concentrated antenna system.

A Proposal of Multi-Carrier Channel Control for Mobile Satellite Communication Systems to Make Maximum Use both of Transponder Bandwidth and Transmission Power

K. Nakahira, T. Sugiyama, H. Nishiyama, and N. Kato

IEICE Trans. on Communications (Japanese Edition), Vol. J95-B, No. 5, pp. 662–676, 2012.

This paper proposes a novel channel control technique for applying the propagation variation condition of mobile satellite earth stations. It is based on adaptive multi-carrier channel allocation (AMCA) that adjusts a modulation method carrier-by-carrier to flexibly utilize the satellite bandwidth and power simultaneously. Since the proposed technique controls transmission power and re-allocates AMCA channels in accordance with the earth station's propagation gain, it enables each of the channel resources needed for communication between stations to be maintained at a minimum level. Simulation evaluation shows that the proposed technique utilizes satellite resources more efficiently than a conventional method that fixes the transmission power for all earth stations. As a result, it enhances the system capacity by about 1.6 times.

Phase sensitive amplification with noise figure below the 3 dB quantum limit using CW pumped PPLN waveguide

M. Asobe, T. Umeki, and O. Tadanaga

Optics Express, Vol. 20, No. 12, pp. 13164–13172, 2012.

The noise figure (NF) of a phase sensitive amplifier (PSA) based on a continuous-wave (CW) periodically poled LiNbO3 (PPLN) waveguide was evaluated in the optical and electrical domains. Phase sensitive amplification was realized using degenerate parametric amplification in the PPLN waveguide, which was pumped by the second harmonic frequency of the signal. Second harmonic pumping enables direct observation of the intrinsic amplified spontaneous emission (ASE), which determined the NF of the PSA. An NF below the 3 dB quantum limit was obtained by observing the intrinsic ASE. The low NF was also confirmed via the noise floor measurement of a cascaded PSA and erbium doped fiber amplifier in the electrical domain. The PSA was used as a preamplifier for detecting a 40 Gbit/s phase shift keying signal. The low noise characteristics were confirmed by the improved sensitivity.

Extendable point-to-multi-point protocol processor for 10G-EPON MAC SoCs

N. Miura, A. Miyazaki, J. Kato, N. Tanaka, M. Urano, M. Nakanishi, and T. Shibata

Proc. of the 2012 IEEE International Symposium on Circuits and

Systems (ISCAS), Vol. 2012, No. 1, pp. 1464–1467, Seoul, Korea.

This paper presents a software-hardware co-operative protocol processor for media-access-control (MAC) system-on-a-chip (SoC) devices in a 10 Gigabit Ethernet passive optical network (10G-EPON), designed with a software-hardware division technique that focuses on the throughput and timing-accuracy requirements. This protocol processor consists of frame-processing hardware to meet the timing requirements, an interface to absorb the speed difference between software and hardware, and software to implement additional protocols. This protocol processor enables network operators to install additional service protocols adaptively for their own services. The 10G-EPON system with this protocol processor worked properly in the experiment.