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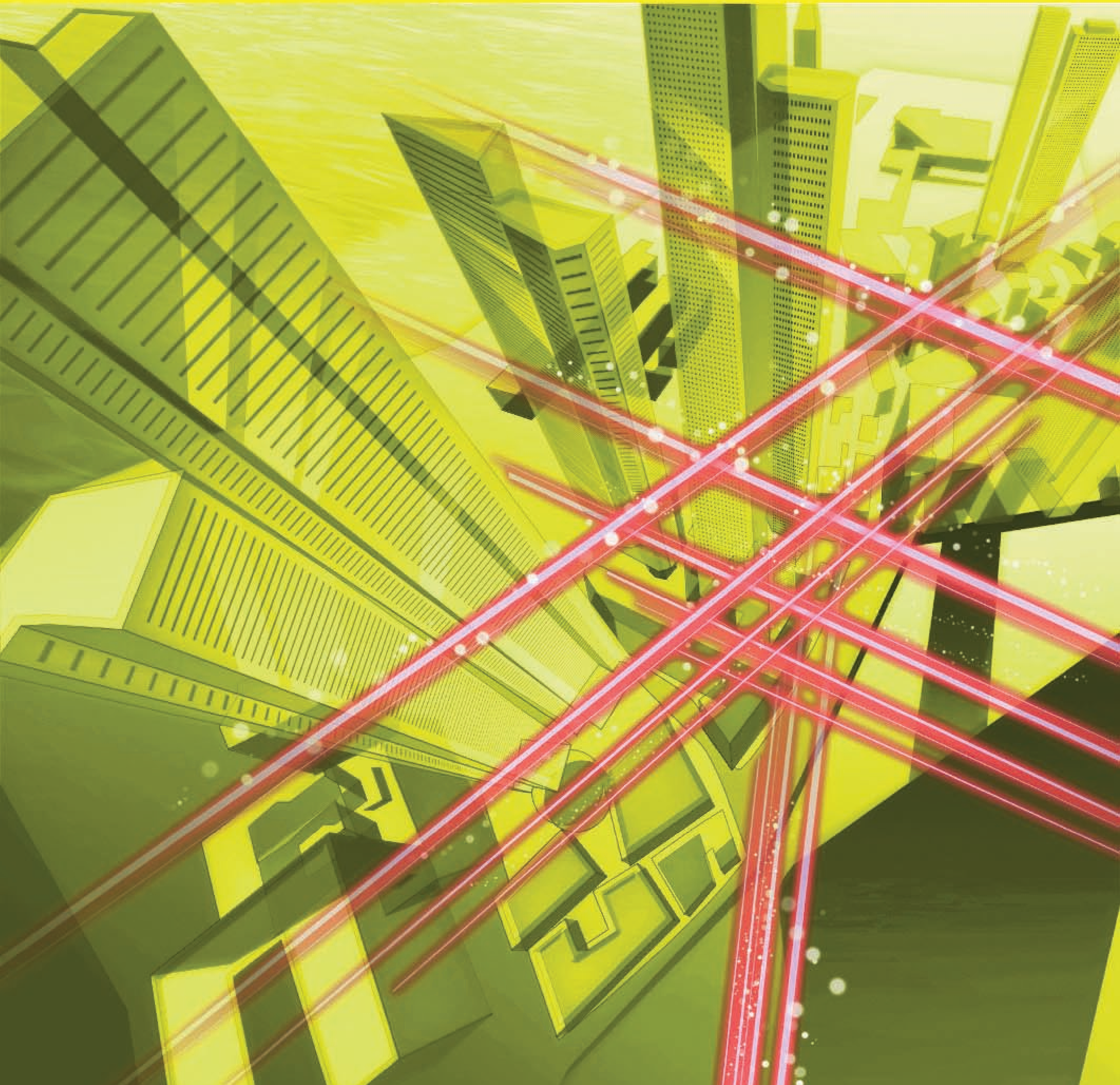

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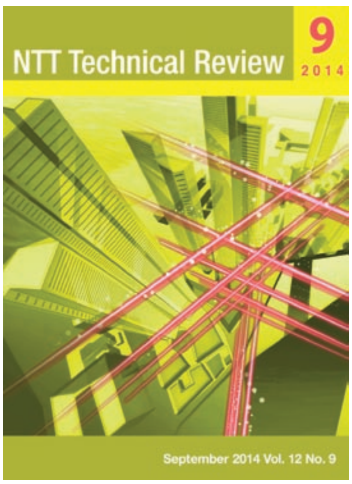

View from the Top

Feature Articles: Frontiers of Quantum Optics Research at NTT Basic Research Laboratories

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Seeing the Forest before Looking at the Trees—Merging Customer Needs with the Power of NTT EAST

Masahide Oka,
Senior Executive Vice President,
NTT EAST

Overview

The telecommunications industry is going through rapid and dramatic changes, and NTT EAST is unveiling a series of innovative policies to cope with this challenging business environment. In this transition to a new mindset, we asked Masahide Oka, Senior Executive Vice President of NTT EAST, to explain to us the logic that the company should use in providing services and the stance that it should take in facing today's challenges.

Keywords: management policy, B2B2C, collaboration

A transition to a new mindset—providing services with a view to the customer's future

—Mr. Oka, can you first update us on the state of business at NTT EAST?

At present, NTT EAST is strategically promoting the penetration of optical broadband. The number of subscribers to the FLET'S HIKARI high-speed optical-fiber connection service had been increasing steadily until three or four years ago, but the emergence of the smartphone and other new devices has forced optical broadband to compete with mobile communications, resulting in slower growth.

To be more specific, the widespread penetration of smartphones and tablets is giving birth to a new "carry ICT with you" lifestyle that is bringing dramatic changes to the market environment. This reflects a change in direction, especially among the young, who want to make ICT a part of their daily life in a more enjoyable and stylish manner.

Under these conditions, NTT EAST has no choice but to change its tactics, and for these last two years or so it has been reviewing and revising sales strategies. As before, they will be active in bringing Internet access to those who are still without it, and they will continue to propose value-added services. At the same time, however, they will turn their attention to new ways of using ICT. That is to say, our efforts to date have been mainly focused on the consumer market in the form of "connecting homes directly to optical broadband." Now, however, considering the intrinsic utility and role of broadband, we must focus once more on providing broadband to corporate enterprises and organizations. In fact, we have redirected our sales strategies to expanding the broadband network not only to large companies but also to small- and medium-sized companies, SOHO (small office/home office) enterprises, and local governments, too.

—Questioning the company's past approach to business seems to indicate a major transition.

That's right—it's not simply a matter of changing our sales target from consumers to companies and thinking that that in itself will reap benefits. For example, our sales department has traditionally asked major electronics and other retailers to appeal to consumers to apply for our FLET'S broadband services, but they simply can't approach the corporate world in the same way. Uncovering the particular problems that companies face, developing an accurate understanding of their management environment, and providing appropriate services all constitute work.

Needless to say, our customers operate in various types of business environments, which means that the number and quality of ICT staff will also differ. It sometimes happens that a company does a good job in setting up network facilities but cannot make good use of them. There are also companies that hesitate to introduce a broadband network due to worries about having to seek support whenever a security issue or operating problem occurs.

With this in mind, we have our sights set on creating a business environment in which our customers can use the network, including follow-up services, with peace of mind. In short, we aim to provide novel services ahead of their time. We are asking all NTT EAST employees to adopt this new mindset. This applies to all aspects of the company including sales practices, systems, technologies, and facilities. It is the sales staff who keep a direct eye on our customers. In the past, they placed a lot of weight on selling telecommunications equipment, but they are now active in hearing about the customer's current business situation and looking to the future. Of course, upper management, to which input from the field eventually reaches, must be able to understand and analyze that input as thoroughly as possible, and in this area, I feel that drastic changes are necessary.

At the same time, we are expanding our efforts in implementing robust disaster countermeasures based on lessons learned from the Great East Japan Earthquake. Last fall, we completed nearly all of the post-earthquake restoration work needed for the immediate future, but we continue to offer assistance to local governments in their restoration planning. What we must not forget here is the need to prepare for the next disaster. We must review countermeasures to disasters that are predicted to occur sometime in the future, such as an earthquake directly beneath the Tokyo metropolitan area. In the Great East Japan Earthquake, our telecommunication facilities were not adversely affected by the earthquake, but they sustained damage from the tsunami and the long-term and widespread power outage that followed. As a result of this experience, we have set up a system that will allow our customers to continue using services without worry even in the event of an earthquake occurring directly beneath the Tokyo metropolitan area.

Responding flexibly to business needs (making a transition from B2C to B2B2C)

—A new approach is being adopted at NTT EAST based on lessons learned. Isn't the "Hikari Collaboration Model" one example of this new mindset?

Our aim is to switch to a business-to-business-to-consumer (B2B2C) model in which end users make use of optical services through our customers' companies. What we want to do here is devise novel services that combine the strengths of our customers' companies with our optical services so that those companies can provide those services directly to end users as products under their own name and brand. We can expect this type of collaboration between our optical services and various types of businesses and market players to result in greater penetration of optical services and to improve the facility utilization rate. Of course, we will continue to apply the traditional B2C model, but going forward, we plan to shift our weight to this new B2B2C model.

—What specific measures are you taking in the network business area to respond flexibly to business needs?

To begin with, we want to be able to respond to the diverse needs of our customers in the business world. In particular, we are working to enhance our network installation capabilities, as in providing bundled installation for multiple sites, time-designated installation, and late-night or early-morning installation. We are currently forming collaborative tie-ups with other companies and investigating the creation of an installation system that can deal as needed with such business needs. Furthermore, to deal with the ever-increasing volumes of traffic brought on by the expanded use of smartphones and tablets and faster transmission speeds, we plan to reduce the per-bit delivery cost by deploying a high-speed, large-capacity optical transmission infrastructure. We also plan to make operations more efficient by reducing on-site maintenance work through the introduction of remote-configuration functions. In these ways, we seek to provide services for business operators and respond flexibly to their diverse business needs.

We also see a need for increasing network reliability. In recent years, cyber attacks have come to occur on a daily basis, and unauthorized accesses to the NTT EAST network have also been increasing. Fortunately, the network has not yet been adversely affected by hacking or other malicious activities, but given the need to boost network reliability in the face of diversifying attacks, we will work to fortify our measures against cyber attacks of all types. We plan to do this in various ways, such as by enhancing our defense and detection functions, upgrading our incident-response system, and developing highly qualified security personnel.

In addition to the above, we are working to improve productivity with the aim of achieving cost-efficient operations. I believe that we have already achieved good results in work that is done off NTT premises by promoting composite work practices. For example, we have maintenance personnel perform systematic facility inspections between fault-repair assignments on customer premises. We are also working to improve productivity even further in work done on NTT premises through a “visualization” mechanism that we developed last fiscal year.

Similarly, we have been engaged in a project to simplify the network since fiscal year 2013, and in this fiscal year, we have been implementing various processes such as those involving circuit switching in order to complete the project. Plus, we are carrying out the circuit switching or circuit removal processes according to the area of NTT base station units and distribution rack units for large buildings. In doing so, we are working to achieve an early power-consumption reduction effect and expand our “green” activities.

Seeing the forest before looking at the trees. The knowledge of researchers holds great promise.

—Mr. Oka, could you leave a message for all NTT EAST employees?

One of my favorite mottos is “Tomorrow is a new day.” It is important that we have the ability to deal with future circumstances, i.e., to have a flexible stance to face whatever comes. Having experienced large and complex projects such as the G8 Hokkaido Toyako Summit as well as unprecedented disasters such as the Great East Japan Earthquake, I believe in the importance of positive thinking. As you know, many facilities collapsed, many lines were severed, and other types of damage occurred when that massive earthquake struck, but at such times, it doesn’t do us any good to just sit around and bewail the tragedy. Rather, it is important that we think about ways of making full use of what is there now, of what remains. Therefore, I have been very encouraged by the NTT

EAST employees who have undertaken their work with a sense of mission based on this idea. I would like everyone to face the future with the same sense of mission.

I would also like everyone to remember that it is equipment, the network, and systems that support services. We already have good results to show for our efforts: we brought the optical coverage rate to 99% as of the end of fiscal year 2013; we completed our work on expanding the NGN (Next Generation Network) and succeeded in maintaining stable operation; and we introduced efficiency-enhancement techniques to reduce costs. A few years ago, for example, we adopted a "total cost" point of view, which means that we manage costs based on the idea that depreciation costs, personnel expenses, and operational costs make up the total cost. That is, if a facility construction project should generate costs, but maintenance and operational expenses then decrease, the total cost should be the same. We have introduced this idea not only in facility work projects but also in the sales and indirect departments with very good results. This is an idea that relates to the future, in which we see the whole forest before looking at individual trees.

Today, the way in which we interact with the world is changing dramatically. I would like everyone to continue with the serious efforts that they have been making so far, but I also want everyone to open a window to society. In sales, for example, we are setting up a system in which we, as an organization, can absorb and learn from the experiences that we have had through direct contact with our customers. I would like everyone to adopt such an attitude to the outside world and connect their experiences to the future.

—Finally, could you also say a few words to NTT researchers?

I would also like our researchers to have such a sense of "seeing the forest before looking at the trees." I expect researchers to offer their knowledge of how to apply current research activities to business. In this regard, I would like to see more discussions taking place between us and researchers than in the past. To all NTT researchers, I would say, "Please demonstrate your full ability at connecting the knowledge of the entire NTT laboratories to our business pursuits."

Interviewee profile

■ Career highlights

Masahide Oka entered Nippon Telegraph & Telephone Public Corporation (now NTT) in 1978. He served as Manager of NTT EAST Tochigi Branch from 2004, as Vice President, Executive Manager, Maintenance and Service Operation Department, Network Business Headquarters of NTT EAST from 2007, and as Senior Vice President, Executive Manager, Maintenance and Service Operation Department, Network Business Headquarters of NTT EAST from 2008. In June 2012, he took up his present position as Senior Executive Vice President of NTT EAST while concurrently serving as Senior Executive Manager, Network Business Headquarters and President of NTT-ME.

Photonic Quantum Information Technologies Explored by Quantum Optics Research

Kaoru Shimizu

Abstract

The quantum nature of light provides us with a novel technology for information processing and communication that is based on the principle of quantum mechanics. The Optical Science Laboratory of NTT Basic Research Laboratories has been engaged in investigating photonic quantum information processing, which involves quantum cryptography and quantum computing. These Feature Articles present the current status of our research activities involving quantum optical state control and the underlying light-matter interaction.

Keywords: photonic quantum information processing, quantum computing, quantum communication

1. Quantum nature of light and photonic quantum information processing

The invention of lasers, which radiate light beams with well-defined waveforms, and of optical fibers, which transmit light beams while preserving their waveforms, has resulted in today's Internet communication environment supported by optical networking technologies. Moreover, various physical characteristics of light are utilized for precise measurement and information interface techniques. Of these, we have not yet fully understood or utilized the quantum mechanical nature of light. Matter is composed of atoms, and an atom consists of elementary particles. In a similar way, light consists of photons, which is an elementary particle that is impossible to divide. The intensity of light corresponds directly to the number of photons.

It is easy to code a photon with a bit of information, 0 or 1, by utilizing the difference between the *horizontal* or *vertical* polarization states. Quantum mechanics represents those states as $|0\rangle$ and $|1\rangle$, respectively. Quantum mechanics prescribes that any quantum state of a photon is represented by a superposed state $|\psi\rangle = a|0\rangle + b|1\rangle$ of $|0\rangle$ and $|1\rangle$. Here, coefficients a and b are called probabilistic amplitudes and are determined in such a way that $|a|^2 + |b|^2 = 1$. The coefficients a and b quantify the overlap of $|\psi\rangle$ with $|0\rangle$ and $|1\rangle$, respectively. This means that no state other than $|1\rangle$ can be completely distinguished from state $|0\rangle$. A set of states $\{|0\rangle,|1\rangle\}$ is called a *basis*, and the choice of basis is not unique. For instance, a set of states $|+\rangle = (1/\sqrt{2})(|0\rangle+|1\rangle)$ and $|-\rangle = (1/\sqrt{2})(|0\rangle-|1\rangle)$ is another basis. The superiority of quantum information processing is attributed to the wide variety of chosen bases that are available depending on the purpose of information processing.

Quantum key distribution relies on the fact that the errorless transmission of a key bit is possible only when the sender and receiver choose the same basis accidentally. An eavesdropper, who is ignorant of their basis choices, unavoidably disturbs the quantum state whenever she tries to access the key bits. By contrast, a sufficiently low error rate estimated for a sample of the key bits convinces the legitimate users of the secrecy of the remaining key bits.

Quantum computing utilizes the fact that many different patterns that are input into a computer can be processed simultaneously by changing the choice of basis. For instance, if the states of photons A and B are $|+\rangle_A$ and $|-\rangle_B$, the whole state is represented by $|+\rangle_A|-\rangle_B = (1/2)\,|0\rangle_A|0\rangle_B - (1/2)|0\rangle_A|1\rangle_B + (1/2)$

$|1\rangle_A|0\rangle_B$ − (1/2) $|1\rangle_A|1\rangle_B$. This suggests that parallel processing takes place for the four different inputs (00), (01), (10), and (11). During the computation, the designed interaction between two photons alters each coefficient value. This precisely describes an operation gate in quantum computing.

As a result, the whole state can evolve to $(1/\sqrt{2})\,|0\rangle_A|0\rangle_B - (1/\sqrt{2})\,|1\rangle_A|1\rangle_B$, which is impossible to factorize. This implies that the states of photons A and B cannot be specified independently and have a certain correlation. Such a state is called an entangled state and is an important resource for quantum information processing. The article "Distribution of Entangled Photon Pairs over 300 km of Optical Fiber" (article 3) [1] describes an example of an entangled state.

2. Four problems in photon manipulation

If we can manipulate a photon in a similar way to an electron, we can easily achieve photonic quantum information processing. However, there are four problematic tasks regarding photon manipulation: (i) generating a photon with certainty whenever necessary, (ii) slowing the photon velocity close to zero, (iii) making two photons interact strongly, and (iv) transmitting a photon without disturbing the quantum state. These problems are difficult to solve with existing technologies.

At first glance, it appears easy to provide a single photon by sufficiently attenuating a laser pulse. However, this inevitably results in a probabilistic distribution as regards the number of photons found in one pulse. Moreover, as the photon has no electric charge, the photon interacts with a material very weakly, and a photon-photon interaction intermediated by the material is not strong enough to alter the photonic quantum state. To cope with the above difficulties, we must gain a deep understanding of light-matter interaction and design and implement an artificial physical process based on it. The articles "Photonic Quantum Information Devices Using Coupled-resonator Optical Waveguides" (article 2) [2] and "Rare-earth Epitaxial Films as a Platform for Quantum Information Manipulation" (article 4) [3] challenge the artificial design of light-matter interaction.

Another approach is to design an information processing scheme that can be achieved with available technologies. The success of quantum key distribution is a typical example of this approach. The unavoidable transmission loss of photons is not crucial for random number distribution. This is because a new random number can be generated even if only the photons that arrive at the receiver's detector are sampled. Hence, we can realize quantum key distribution by using a highly attenuated laser pulse. Thus, designing a new scheme or protocol is very important in addition to studying the physical process. For instance, there are many different possible ways to encode a bit of information in a photon other than using the polarization state.

3. Research trends in photonic quantum information processing

For the past ten years, quantum key distribution has been the main research topic of the Optical Science Laboratory. Our research interest has now shifted to practical considerations regarding actual use. Hence, the main target of our basic research has changed to the study of (i) a quantum repeater system for extending the quantum communication distance and (ii) the photonic implementation of quantum circuits. To progress with these research topics, we must cope with the four problems mentioned in the previous section. The following briefly introduces each topic covered in these Feature Articles.

Article 2 relates to a novel technique for slowing the velocity of light to increase the interaction time of photons in a nonlinear optical medium. This is a solution to the second and third problems. As a result, the photon pair generation rate is greatly improved. This offers a solution to the first problem. This is because we can ensure the certain emission of one photon by detecting another photon. The latter part of the article introduces a technique for adjusting the temporal position of photons, which makes it possible to synchronize many photons launched into a quantum circuit. The above techniques are implemented with a photonic circuit integrated on a small-size silicon chip. This guarantees the temporal stability necessary for quantum computing. Article 3 describes the photonic realization of an entangled quantum state. Quantum correlations between two photons are confirmed even when photons are 300 km apart in optical fibers. The preserved entangled quantum state has convinced us of the technical feasibility of long-distance quantum entanglement distribution.

Article 4 and article 5, "Investigating the Properties of Glasses Using High Resolution Spectroscopy of Er^{3+} Ions" [4], correspond to the second problem, where a photon is stored in a medium and then retrieved. The medium works as a photon memory. The quantum state of the photon is correctly transferred to the electron in the medium and vice versa.

Such a technique has already been demonstrated with laser-cooled atomic gases. However, there is no atomic species available for the 1.5-μm optical communication wavelength. Hence, we employ a solid-state medium doped with erbium (Er^{3+}) ions, which has an optical transition line at a wavelength of 1.5 μm. Article 4 first explains why a crystal doped with erbium ions is expected to be a candidate for a photon memory, and then reports the fabrication and characterization of a novel erbium doped material, Er_2O_3. Article 5 presents an interesting phenomenon peculiar to glasses that we found by observing the quantum state of silica optical glass fiber doped with erbium ions.

The sixth article, "A Bose-Einstein Condensate Achieved on a Persistent-supercurrent Atom Chip" [5], introduces an alternative approach to quantum information processing, where we employ condensed gases of ultra-cold atoms instead of photons. The first step is the realization of a Bose-Einstein condensate of cold atoms, which is confined by a strong and stable magnetic field supported by a persistent superconducting current in a chip-size loop circuit. Fifty-thousand identical atoms occupy the same quantum state, which behaves as a matter wave.

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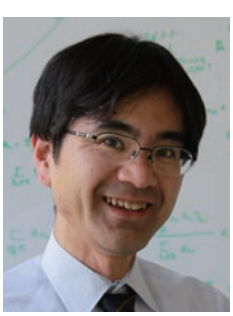

Kaoru Shimizu

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He received the B.E., M.E, and Ph.D. in applied physics from Waseda University, Tokyo, in 1988, 1990 and 1995, respectively. He joined NTT Transmission System Laboratories in 1990 and moved to NTT Basic Research Laboratories in 1996. His research interest involves quantum information processing including quantum communication, quantum cryptography, and quantum memory devices. He is a member of the Physical Society of Japan.

Photonic Quantum Information Devices Using Coupled-resonator Optical Waveguides

Nobuyuki Matsuda, Hiroki Takesue, William John Munro, Eiichi Kuramochi, and Masaya Notomi

Abstract

Integrating a quantum circuit on a small photonic chip offers the promise of large-scale quantum information processing using photons. In this article, we review our research and development of integrated quantum information devices using silicon photonic crystal technology.

Keywords: quantum information, photonic crystals, slow light

1. Introduction

Photons are excellent carriers of qubits, which are substantial resources for quantum information processing (QIP) technologies [1]. The application of QIP includes quantum computation, where there are known tasks that can be performed significantly faster compared to what can be achieved on today's conventional classical machines. The tasks could include simulation, factoring, searching, and so on. As is predicted from the current classical computers, it will be necessary to miniaturize and integrate QIP devices on a small chip. This implementation can be done by using integrated photonics technology such as silica-based planar lightwave circuits and silicon photonic circuits, which for many years have been developed for telecommunications applications by many institutions including NTT. For instance, we can achieve a quantum logic gate for quantum computation by exploiting directional couplers (beam splitters) [2], which are fundamental devices widely used in optical communication. Consequently, much research is being done on developing a QIP system using integrated photonics technologies.

A typical integrated quantum system is schematically depicted in **Fig. 1**. The system has three main building blocks: quantum light sources that generate non-classical light such as a single photon or entangled photons [3, 4]; a linear-optical quantum circuit that manipulates quantum states encoded in the photon's physical degrees of freedom [5]; and single-photon detectors. Here, we achieved a light source and a new component for the circuit using silicon photonic crystal nanocavities [6]. Thanks to a strong

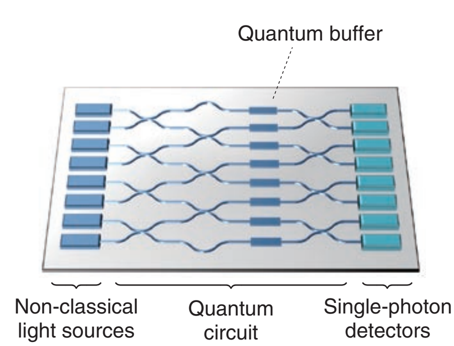
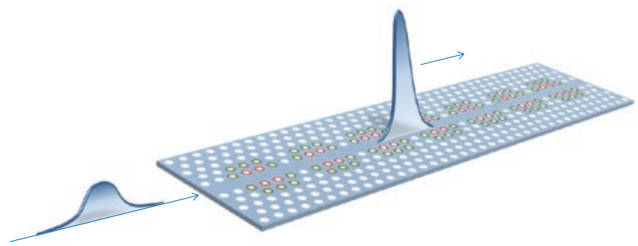
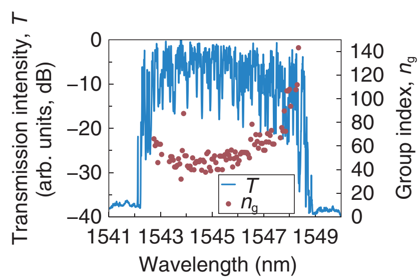


Fig. 1. Schematic illustration of integrated quantum information system.



(a) Schematic of photonic crystal CROW (7 nanocavities) displayed with propagating optical pulses



(b) Transmission and group-index spectra of CROW with 200 cavities

Fig. 2. (a) Schematic of photonic crystal CROW and (b) CROW spectra.

light confinement feature achieved in photonic crystals, we realized ultra-compact photonic components on a chip. Moreover, we successfully improved the efficiency and the functionality of those devices by exploiting the slow-light mode that arises in nanoscale photonic crystals [7, 8].

2. Silicon photonic crystal coupled-resonator optical waveguides

We use coupled-resonator optical waveguides (CROWs) consisting of photonic crystal nanocavities [5]. A CROW is a waveguide consisting of optical cavities that are nearest-neighbour coupled along a one-dimensional direction. The chain of optical cavities induces a collectively resonant mode, whose properties (bandwidth and dispersion) can be strongly modulated by controlling the strength of the inter-cavity couplings. This feature is unlike that of conventional optical waveguides whose guiding properties are dominated by lateral confinement structures. Because of this feature, we can design CROWs to realize a large-bandwidth waveguide for high-speed signal transmission, or a small-group velocity waveguide for buffering optical signals depending on the application.

A schematic of our photonic crystal CROW is shown in **Fig. 2(a)**. The CROW is fabricated on a 210-nm-thick silicon top layer of a silicon-on-insulator wafer. The photonic crystal is formed by triangular-lattice air holes 105 nm in diameter and with a lattice constant *a* of 420 nm. Each optical cavity is formed by the local width modulation of a line defect in the photonic crystal. The colored holes are shifted by a few nanometers in-plane toward outside. This width modulation yields a cavity mode with a cavity *Q* greater than one million [9].

We show transmission and group index spectra of our CROW in **Fig. 2(b)**. Here, the group index n_g is the group velocity in a vacuum *c* divided by the group velocity in the media. The CROW exhibits $n_g \approx 40$ in a passband as wide as 6 nm. The CROW has low loss thanks to the ultrahigh *Q* of individual cavities, which suppresses the out-of-plane scattering of the propagating optical field [9]. In addition, our nanofabrication accuracy is high enough that the propagation mode is less influenced by a localized mode caused by structural disorder [10]. As a result, we successfully achieved light propagation in a CROW up to 400 cavities, which is the largest scale to date.

3. Slow-light-enhanced generation of correlated photon pairs

The non-classical light source includes a correlated photon pair source, which generates a pair of photons that correlate in their generation time. For the generation, we can use a spontaneous four-wave mixing

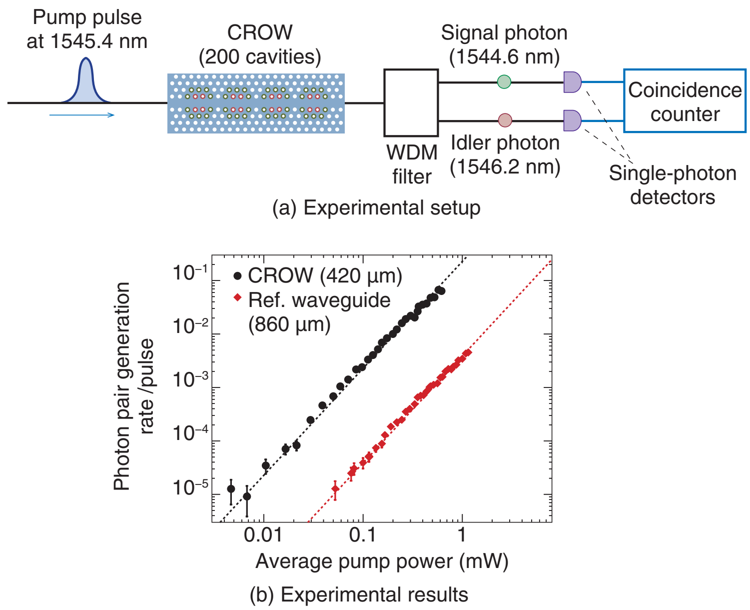


Fig. 3. Slow-light-enhanced correlated photon pair generation using CROW.

(SFWM) process, which is a third-order nonlinear effect. By injecting a pump laser with an appropriate wavelength into a nonlinear waveguide, we can create correlated twin photons after annihilating two photons in the pump field. This process obeys the conservation law of energy and momentum between the four involved photons. Here, we call the generated twin photons a signal photon and an idler photon.

We can enhance the nonlinear optical effect per unit device size using slow-light propagation. This is because, first, the slow-light mode simply prolongs the light-matter interaction time by a factor of n_g. Second, the slow-light mode compresses the optical field along the propagation axis such that its peak intensity increases by a factor of n_g. As a result, the nonlinear constant γ(/W/m), which is a typical measure of the strength of waveguide nonlinearity, is proportional to n_g^2. Our experiment demonstrated γ= 13,000/W/m at $n_g \approx 49$ [11]. This value is the highest ever reported in any silicon-core nonlinear waveguides. This value also indicates that a 1-mm-long CROW yields nonlinearity that is as strong as that of a 10-km-long optical fiber.

We attempted to improve the generation efficiency of photon pairs via SFWM using the slow-light effect. The experimental setup is schematically depicted in **Fig. 3(a)**. We injected pump pulses with a center wavelength of 1545.4 nm to the CROW. Photon pairs generated in the CROW are separated by the wavelength-division-multiplexing (WDM) filter into two different optical paths, and subsequently received by the single-photon counting modules (SPCMs). The pair generation rate can be estimated by a coincidence measurement of the detection signals from the two SPCMs.

The experimental results are shown in **Fig. 3(b)**. We see that the generation rate is proportional to the square of the pump power. This is because the photon pair generation in SFWM is caused by the simultaneous annihilation of two photons in the pump field. We also performed the same experiment using a reference line-defect photonic crystal waveguide ($n_g \approx 6$) fabricated on the same chip. From Fig. 3(b), we observe that the pair generation rate from the CROW is two orders of magnitude larger than that from the reference waveguide. The enhancement can be explained by the differences in the n_g values and the length of the waveguides. We obtained a pair generation rate of 0.1 per pump pulse at an average pump power of less than 1 mW; this generation rate is high enough for the photon pair source based on spontaneous processes. Thus, we successfully enhanced the photon pair generation rate by almost 100 times using the slow-light effect in the CROW [6].

We further demonstrated the efficient generation of entangled photons from the CROW [12]. Quantum entanglement is a key resource for many QIP protocols. This is a key technology to realize a compact

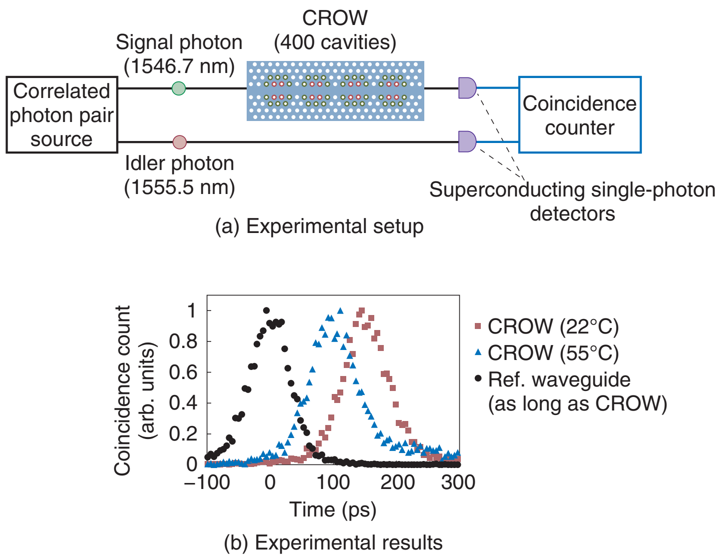


Fig. 4. Single-photon buffer experiment using photonic crystal CROW.

on-chip entangled photon source required for large-scale quantum information systems.

4. On-chip quantum buffer

The quantum circuit shown in Fig. 1 consists of arithmetic elements such as quantum logic gates, for which we can use the quantum interference effect between two identical photons on a directional coupler (*i.e.*, beam splitter) [2]. In doing so, we have to synchronize the arrival times of the photons generated from different sources at the directional coupler. Such synchronization can be achieved by means of a quantum buffer, which is capable of actively controlling the propagation time of a photon without degrading its quantum properties.

We created a quantum buffer using the photonic crystal CROW [8]. The experimental setup is shown in **Fig. 4(a)**. We inserted a CROW in the optical path of the signal photon before the photon pair detection at the SPCMs. We performed the coincidence measurement and obtain an arrival time difference of the correlated photons. We observed this arrival time difference with and without the CROW. To obtain the high temporal resolution necessary to discriminate the arrival time difference, we used superconducting single-photon detectors, which have a high temporal resolution as well as a high signal-to-noise ratio.

The experimental result is shown in **Fig. 4(b)**. The horizontal axis indicates the arrival time difference of the pair of photons; that is, it indicates the extent of the delay of the signal photons with respect to the arrival of the idler photons. The vertical axis is a coincidence count normalized with respect to the peak count rate. For a reference, we used the same line-defect photonic crystal waveguide as the one used in the experiment described in section 3. We set the arrival time difference for the reference waveguide to the origin of the horizontal axis. By replacing the reference waveguide with the CROW, we observed a clear delay—as much as 150 ps—of the arrival time of the signal photons. Hence, we successfully demonstrated a single-photon delay line on a chip. A clear transmission signal was obtained even with the CROW with 400 cavities thanks to the ultrahigh Q value of each photonic crystal cavity.

We conducted another experiment to actively control the buffering time. To achieve this, we exploited the wavelength dependence of n_g shown in Fig. 2(b). The n_g spectrum can be shifted along the wavelength axis simply by varying the temperature of the CROW. In this way, we can change the n_g of the CROW without changing the wavelength of the signal photon. We show the coincidence waveform at the chip temperature of 55°C. The delay time is approximately 103 ps. Thus, we achieved delay tuning of the single-photon wave packets over approximately 50 ps.

Furthermore, we also confirmed that the chip was able to buffer one of the entangled photons. The time-bin entanglement encoded in the correlated photons was successfully stored for 150 ps without any degradation of the degree of entanglement. This experiment suggests that we can readily utilize our on-chip quantum buffer for storing and retrieving photons that possess qubit information.

5. Summary and outlook

We reported on-chip quantum photonic devices using the slow-light effect in a silicon photonic crystal CROW. We have shown that photonic crystal technology can increase the efficiency and functionality of building blocks for integrated photonic quantum information processing. To fully achieve the integrated QIP system, it is also necessary to integrate a WDM filter for the photon pair source and single-photon detectors. We aim to monolithically integrate the quantum subsystems in our efforts to realize a large-scale photonic QIP system.

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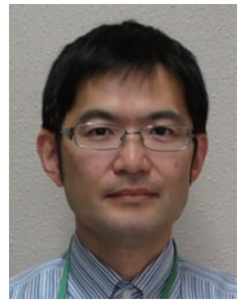

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Distribution of Entangled Photon Pairs over 300 km of Optical Fiber

Takahiro Inagaki and Hiroki Takesue

Abstract

We describe our recent experiment on the distribution of time-bin entangled photon pairs over 300 km of optical fiber, which set a record for long-distance distribution of quantum information. This experiment was achieved by using a high-speed and high signal-to-noise ratio entanglement generation/evaluation setup consisting of periodically poled lithium niobate waveguides and superconducting single-photon detectors. We observed the violation of Bell's inequality and thus confirmed that the entangled photon pairs preserved the quantum correlation after they were separated by 300 km of fiber.

Keywords: quantum communication, quantum cryptography, entanglement

1. Introduction

A huge calculation time is required in order to solve certain mathematical problems such as factorization. The security of most modern cryptography schemes is ensured by achieving a high difficulty of solving such mathematical problems. The progress made in computers and algorithms, however, means that the calculation time may be drastically reduced in the future. Quantum cryptography, or quantum key distribution (QKD), has been proposed as a secure communication scheme based on a law of physics [1]. In a QKD system, a random key for a one-time pad cryptographic system is distributed from a sender (Alice) to a receiver (Bob) by sending single photons. According to Heisenberg's uncertainty principle, a quantum state cannot be duplicated completely. This fundamental rule of physics protects the random key against eavesdroppers. When the eavesdroppers intercept the single photons and measure them to steal the information, the measurement inevitably disturbs the quantum states of the photons, which results in errors in the photon transmission between Alice and Bob. In this way, we can detect the eavesdropping by monitoring a change in the error rate and ensure the security of the random key.

QKD with a weak coherent light has already been implemented in field experiments at communication distances of tens of kilometers. A video-conference service based on QKD, for example, was demonstrated in the Tokyo QKD network in 2010 [2]. To increase the key distribution distance further, however, the loss in the communication channel is a primary issue that must be addressed. When we send a single photon over optical fiber, roughly 5% of the photons are lost in the optical fiber per 1-km transmission. This means that the success probability of the single-photon transmission over 300 km of optical fiber is less than 0.0001%. When the photon count rate becomes comparable to a dark count rate of a single-photon detector because of the transmission loss, we can no longer distinguish the transmitted signal. Hence, the communication range of the QKD is limited by the signal-to-noise ratio (SNR). Unfortunately, we cannot use an optical amplifier for the QKD because we also cannot duplicate the single photon without any errors.

Consequently, entanglement-based QKD has been proposed as a way to improve the SNR in long-distance QKD [3]. In this scheme, an entangled photon pair is distributed to each distant receiver from a halfway point of the communication channel. The success probability of the single-photon transmission increases because the transmission distance of each photon is reduced by half, and thus, we can improve the SNR compared with the conventional QKD. The

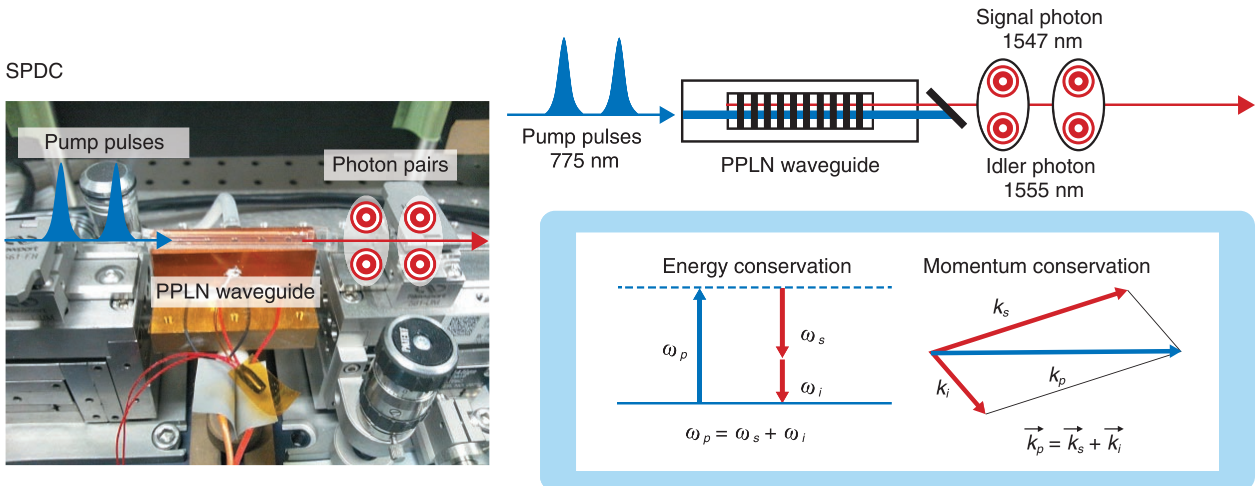

Fig. 1. Spontaneous parametric down conversion in PPLN waveguide.

quantum entanglement is a quantum state where each particle cannot be described as a quantum state independently. When we undertake a measurement on an entangled photon pair, the result for each photon is completely random, but the two results show a correlation, even when these two photons are separated by long distances. This correlation, which cannot be explained by classical theory, is an essential property of quantum entanglement.

NTT demonstrated entanglement-based QKD over 100 km of optical fiber in 2008 [4] and also performed long-distance entanglement distribution over 200 km in 2009 [5]. In this article, we introduce our recent experimental results for entanglement distribution over 300 km of optical fiber [6].

2. Generation and measurement of entangled photon pairs

For the long-distance entanglement distribution, we generate high-dimensional time-bin entangled photon pairs, which are suitable for fiber transmission [7]. We employ a spontaneous parametric down conversion (SPDC) process in a periodically poled lithium niobate (PPLN) waveguide to generate temporally correlated photon pairs, as shown in **Fig. 1** [8]. The two generated photons, which are called signal and idler photons, conserve the total momentum and energy of the pump photon. In time-bin entangled state generation, we input coherent sequential pulses into the PPLN waveguide as a pump. If the pump power is small, and the probability that these pulses will generate photon pairs simultaneously is relatively small, we can generate a coherent superposition state of the photon pair states generated by those pump pulses. The whole state wave function of an entangled photon pair can be written approximately as:

$$|\psi\rangle=\frac{1}{\sqrt{N}}\sum_{k=1}^{N}|k\rangle_s|k\rangle_i \, , \qquad (1)$$

where $|k\rangle_z$ denotes a state in which a single photon is found at the kth time slot in mode z (= s: signal, i: idler). Here, N is the number of pulses in which the phase coherence of the pump pulses is preserved. The generated signal and idler photons are separated by a wavelength filter and then launched into long-distance fibers.

After the long-distance distribution of the entangled photon pair, we evaluate the distributed entanglement by measuring two-photon interference in a Franson-type experiment [9]. The distributed signal and idler photons are measured with n-bit delayed Mach–Zehnder interferometers (MZIs) followed by single-photon detectors. The n-bit delayed MZIs transform the $|k\rangle_z$ state into the $|k\rangle_z + \exp(i\theta_z)|k + n\rangle_z$ state (unnormalized), where θ_z is the relative phase between the two divided paths in each MZI. Under the condition of $N >> n$, the coincidence count rate between the signal and idler photons is approximately proportional to $1 + V\cos(\theta_s + \theta_i)$, where V is the visibility of the two-photon interference. In measuring the entanglement, although the photon count rate of the signal and idler photons is independent of the MZI phases, we will observe a change in the coincidence count between the signal and idler photons depending on the phases of the MZIs.

We also confirm the violation of Bell's inequality to make sure that the two-photon interference is caused by the quantum mechanics. In the Bell's inequality experiment, we measure a criterion value of S for the Clauser, Horne, Shimony, and Holt (CHSH) inequality [10]: $|S| \leq 2$ for any correlations based on the classical mechanics. The S value is obtained by undertaking 16 coincidence count measurements, in which the 4 different phase values of MZIs are set for the signal and idler photon detection. The S value is given by

$$S = E(d_s,d_i) + E(d_s,d_i') + E(d_s',d_i) - E(d_s',d_i') , \quad (2)$$

where d_z, d'_z ($z = s, i$) denote arbitrary values of phases θ_z in interferometers, and $E(\theta_s,\theta_i)$ is defined as:

$$E(\theta_s,\theta_i) := \frac{R(\theta_s,\theta_i) - R(\theta_s,\theta_i+\pi) - R(\theta_s+\pi,\theta_i) + R(\theta_s+\pi,\theta_i+\pi)}{R(\theta_s,\theta_i) + R(\theta_s,\theta_i+\pi) + R(\theta_s+\pi,\theta_i) + R(\theta_s+\pi,\theta_i+\pi)} \cdot (3)$$

Here, $R(\theta_s, \theta_i)$ is the coincidence count rate of a two-photon interference measurement when we set the phases of the MZIs for the signal and idler photons at θ_s and θ_i, respectively. Although the S value obtained in a measurement on any classically correlated photons does not exceed 2, the value for an entangled photon pair can be larger than 2 by selecting appropriate phase settings (violation of Bell's inequality). Thus, we can distinguish between the correlations based on the quantum and classical mechanics depending on whether or not the obtained S value exceeds 2, respectively.

3. Experimental setup

Our experimental setup is shown in **Fig. 2**. The high-dimensional time-bin entangled photon pairs were generated by the SPDC process in the PPLN waveguide. We set the repetition rate of the sequential pump pulses as high as 2 GHz so that we can use the time domain efficiently. The generated signal and idler photons were separated by a wavelength filter and then launched into 150-km dispersion-shifted fibers. The distributed photons were launched into MZIs fabricated based on planar lightwave circuit technology. The propagation time difference between the two paths of the MZI was 1 ns, and thus, it worked as a 2-bit delay for 2-GHz repetition pulses. We were able to control the phases of θ_s and θ_i by tuning the temperature of MZI-1 and MZI-2, respectively. An output port of each MZI was connected to a superconducting single-photon detector (SSPD), which contributed to the low-noise and highly efficient detection of the entangled photon pairs. The SSPD had a low dark count probability of about 1×10^{-9} per 100-ps time window and a high detection efficiency of 20%. Output signals from the SSPDs were input into a time interval analyzer (TIA) as the start and stop signals for coincidence detection. The time resolution of the TIA was 9.8 ps, and the coincidence counts were collected in a 300-ps time window.

4. Two-photon interference and violation of Bell's inequality

The experimental results of the two-photon interference by the distributed entangled photon pairs are shown in **Fig. 3**. First, we fixed θ_s by setting the temperature of MZI-1 at 15.35°C and swept the temperature of MZI-2 in 0.1°C steps while measuring the coincidence counts. The measurement time was 1 hour for each temperature setting. The corrected coincidence counts, which are raw data without the subtraction of accidental counts, are shown by the circles in Fig. 3, which show a clear sinusoidal modulation. The visibility of the fitted curve was 86.1 ± 6.8%. We then changed θ_s with the temperature of MZI-1 at 15.54°C and observed another fringe (squares), whose visibility was 83.7 ± 9.1%. Thus, we confirmed that a non-classical correlation was preserved even after the two photons were separated by as much as 300 km of fiber.

We then performed the S value measurement for the CHSH inequality. We searched for phase settings where the coincidence rate was maximized, and we defined these phases as θ_{s0} and θ_{i0}. We used these phases to determine the measurement parameters in Eq. (2) as $d_s = \theta_{s0}$, $d'_s = \theta_{s0} + \pi / 2$, $d_i = \theta_{i0} + \pi / 4$, and $d'_i = \theta_{i0} - \pi / 4$. We obtained 16 values of $R(\theta_s, \theta_i)$ over 16 hours to obtain the S value. To improve the accuracy of the S value, we repeated the same experiments three times with the same measurement parameters. As a result, we found that $S = 2.41 \pm 0.14$, leading to the violation of 2.9 standard deviations. This means that the correlation of the entangled photon pair clearly violates Bell's inequality. We confirmed from this result that we achieved a high-quality entanglement distribution over 300 km of fiber.

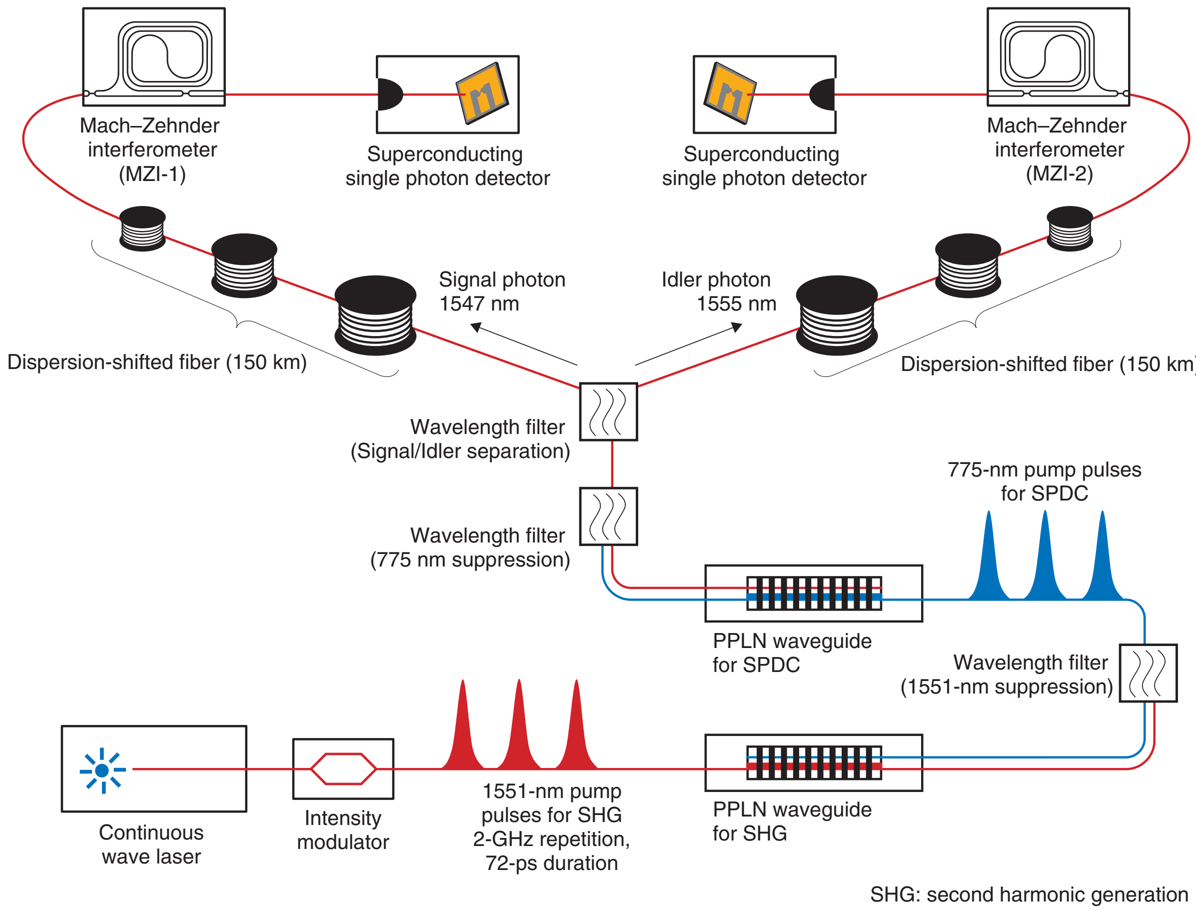

Fig. 2. Experimental setup for distribution of time-bin entangled photon pairs over 300 km of optical fiber.

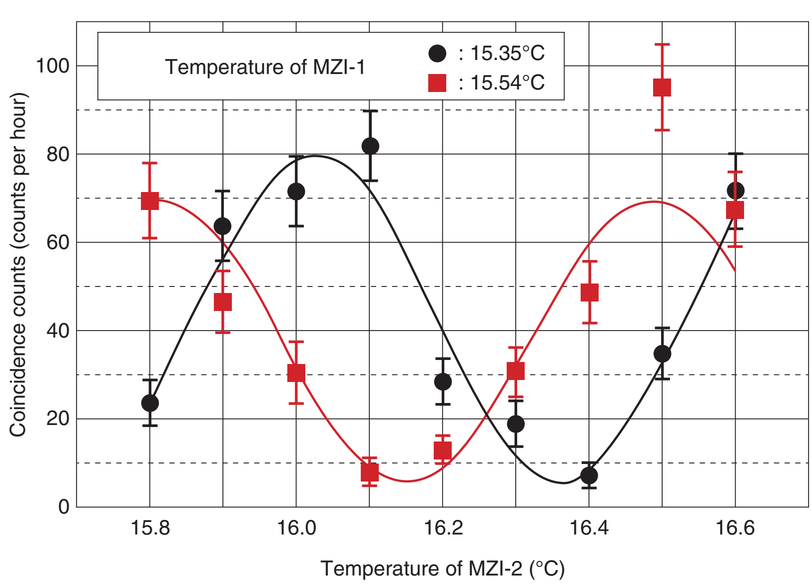

Fig. 3. Two-photon interference fringes obtained after 300-km distribution over fiber.

5. Future work toward long-distance entanglement distribution

The distance of the entanglement distribution is limited by the SNR of the setup, in principle. It is possible to attempt a longer distance distribution as long as the noise in the system is sufficiently low. Even if we can ignore the noise, however, the success probability of the distribution decreases exponentially as the distance increases, and thus, the time required for the distribution also increases exponentially. To solve this problem, Briegel et al. proposed the concept of a quantum repeater [11] based on nested entanglement swapping [12], entanglement purification, and quantum memory. The quantum memory is a key device for the quantum repeater, as it can store the quantum state of the distributed photon and output it after an arbitrary time. NTT has been studying several kinds of quantum memories as part of efforts to realize a quantum repeater. These memories include an atomic ensemble in a solid-state material. In the future, we hope to realize long-distance quantum communication by combining our entanglement generation and distribution technologies with quantum memories.

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Rare-earth Epitaxial Films as a Platform for Quantum Information Manipulation

Takehiko Tawara and Hiroo Omi

Abstract

Rare-earth ions in a solid form have discrete energy levels peculiar to the ionic species, and they are therefore expected to become an excellent platform material for quantum information manipulation. A promising candidate for this purpose is rare-earth epitaxial film such as erbium oxide (Er_2O_3) film grown on a silicon substrate. This article describes the high-quality crystal growth and excellent optical characteristics of Er_2O_3 epitaxial films for quantum information devices.

Keywords: erbium oxide, population manipulation, energy transfer

1. Introduction

In traditional telecommunication and data processing, information is transmitted as a classic light and voltage signal. However, we can expect the transmission quantity or speed with this approach to reach its limit in the near future. Today, information communication and processing techniques using photons and electrons based on the principles of quantum mechanics are being actively studied to overcome this limitation problem.

The following methods are commonly used for quantum information communication and processing. Quantum information is transferred via optical polarization of a photon or electron spin state in a given material. A photon is used for the spatial transmission of information, and an electron is suitable for memory and information processing applications. The quantum information is exchanged between photons and electrons and manipulated by the photon-electron interaction. A critical issue with such a protocol is finding a way to improve the reliability of the exchanges and manipulation. Therefore, the selection of the material systems for the electron platform and the application of a suitable exchange and manipulation mechanism are especially important.

Various materials and interaction mechanisms have already been proposed. Among these, we focus on stimulated Raman adiabatic passage (STIRAP), which uses three quantum levels as the principle of interaction (**Fig. 1**). In the STIRAP scheme with a lambda-type three-level system, the electron is initially in state |1>. After the irradiation of laser pulse 1, which leads to coupling between states |2> and |3>, the delayed laser pulse 2 (a photon with quantum information) causes excitation between states |1> and |2>, and the quantum information of this pulse is copied to an electron. Then the electron at state |1> transfers coherently to state |3> without passing state |2>. Here, a theoretical transfer efficiency of almost 100% is expected, and the quantum information of an electron can be maintained at state |3>, which has a long decay time [1]. Reverse transfer (from |3> to |1>) is also possible by using the opposite pulse sequence. Moreover, if another state (|4>) is prepared, a quantum bit as the information can be operated by employing STIRAP twice. That is, three (or four) ideal quantum levels that can interact with a photon enable the manipulation of all the quantum information [2].

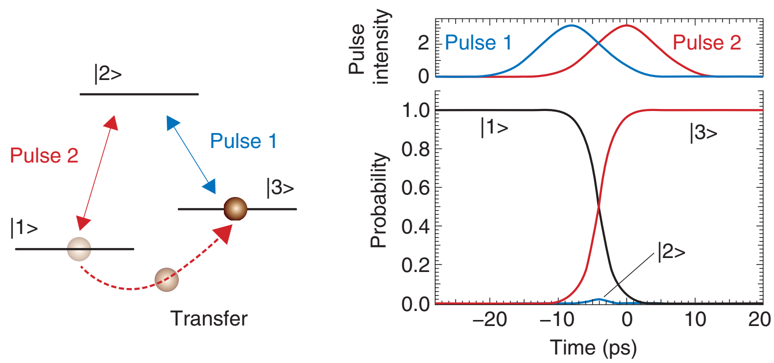


Fig. 1. STIRAP with lambda-type three-level system.

2. Characteristics of rare-earth materials

What material system is suitable for quantum information manipulation based on STIRAP? Until now, this issue has been studied mainly using trapped atoms. While these are an ideal platform with deterministic, discrete, and non-perturbable quantum states, the equipment setup is complicated, and they are unsuitable for device applications. Semiconductor nanostructures such as quantum dots can be considered as other candidates that are advantageous for device application. However, it is difficult to prepare an ideal quantum level because of the quantum level energy fluctuation caused by the inhomogeneity of the structure and the energy broadening caused by a strong interaction with the crystalline environment.

In contrast, rare-earth-doped solids are attractive as a robust material system for population manipulation in a solid, because they form deterministic and discrete quantum levels that do not depend on either host material or temperature. The intra-4*f* orbitals in rare-earth ions are weakly perturbed by the crystalline environment (**Fig. 2(a)**), and they form ideal quantum levels with only slight energy fluctuation.

Erbium (Er) is a well-known rare-earth ion that is widely used in erbium-doped optical fiber amplifiers (EDFAs) in existing optical communications networks. The intra-4*f* orbital of an Er ion forms quantum levels that can interact with telecom-band photons (transition between $^4I_{13/2}$ and $^4I_{15/2}$ manifolds). Therefore, Er-based materials are very promising as a platform of STIRAP, and we are focusing in particular on epitaxial erbium oxide (Er_2O_3) thin films. [3] We have three reasons for this:

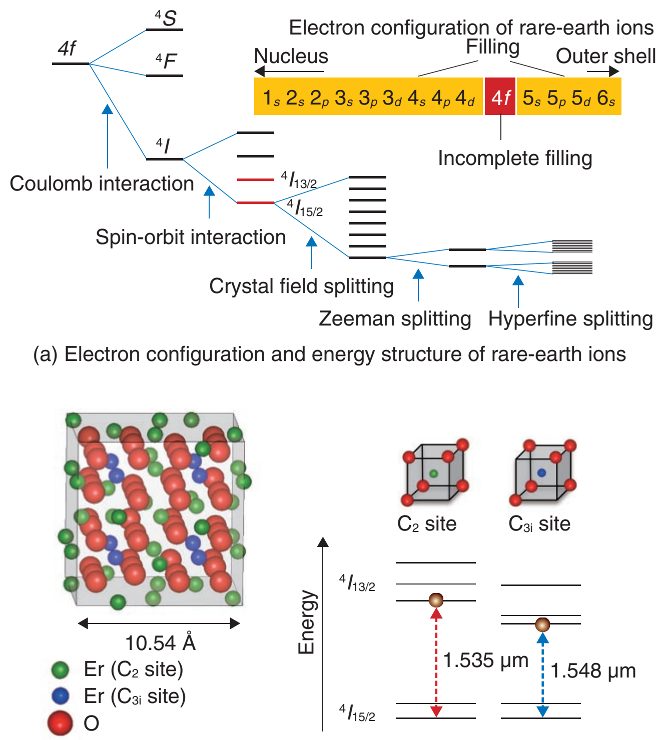
1. They have the highest concentration of Er ions per unit volume (2.7×10^{22} cm^{-3}).
2. The intra-4*f* transition in Er ions is activated by coupling with oxide ions.
3. The lattice constant of Er_2O_3 matches that of Si(111).

In conventional Er-doped crystal, concentration quenching is induced by defects when the Er ions are highly doped. On the contrary, in epitaxial Er_2O_3 thin films grown on a Si substrate, the generation of crystal defects is strongly suppressed without concentration quenching. Moreover, epitaxial Er_2O_3 on a Si substrate will enable on-chip integration with other functional devices such as light sources or detectors.

The crystal structure of Er_2O_3 is shown in **Fig. 2(b)**. The Er ions in this structure have two different sites with different symmetries, namely C_2 and C_{3i}. Because the crystal field differs at different sites, the energy levels also differ slightly between the C_2 and C_{3i} sites. In other words, the Er ion site that interacts with photons can be chosen by tuning the photon wavelength.

3. Fabrication of epitaxial Er_2O_3 on Si(111) substrates

An 85-nm-thick Er_2O_3 crystal was grown on a pure Si(111) surface by molecular beam epitaxy (MBE) at the optimum growth temperature and beam flux. As shown in **Fig. 3**, a cross-sectional transmission electron microscope (TEM) image obtained after growth proves that the Er_2O_3 was grown epitaxially on the Si(111) surface without any crystal defects. This is also proved by the X-ray diffraction pattern. Thus, we succeeded in growing epitaxial Er_2O_3 thin films with high crystalline quality on Si(111) substrates.



(a) Electron configuration and energy structure of rare-earth ions

(b) Crystal structure and optical transition of Er_2O_3

Fig. 2. Properties of rare-earth ions and erbium oxide.

4. Population dynamics in discrete energy levels

To characterize the quantum energy levels, we measured the photoluminescence (PL) spectrum of the grown Er_2O_3 samples at various excitation wavelengths [4] (**Fig. 4**). If the excitation wavelength corresponds to the Er_2O_3 energy level, the excitation photons are absorbed by electrons with the transition from the ground state of the $^4I_{15/2}$ manifold to the excited state of the $^4I_{13/2}$ manifold. After a certain lifetime, these excited electrons relax to the ground state with the photon emission. When the energy level does not agree with the excitation wavelength, since there is no photon absorption, the luminescence does not appear either. In the color plot in Fig. 4(a), when the figure is sliced in the vertical (horizontal) axis direction, it is equivalent to an absorption (emission) spectrum. The absorption spectrum detected at an emission wavelength of 1548 nm, which corresponds to the lowest energy transition of the C_{3i} site (Fig. 4(b)), clearly reveals the formation of discrete and sharp energy levels. Since intense luminescence is also observed in the PL spectrum, concentration quenching is strongly suppressed by high quality epitaxial films without defects. The absorption peaks can be assigned to each energy level of the C_2 and C_{3i} sites by referring to theoretical analysis and experimental results for Er-doped materials. The absorption linewidth (full width at half maximum) is as narrow as 200 μeV. Since this is much narrower than the energy intervals of the $^4I_{13/2}$ manifold, we can access each energy level optically.

Interestingly, these emissions from the C_{3i} site appear even though the excitation energy resonates with the energy levels of the C_2 site, which is separate from the C_{3i} site. For instance, the peak with the red arrow labeled 1 in Fig. 4(b) indicates that both the strong absorption at the C_2 site and the emission from the C_{3i} site appear simultaneously. This means that energy is transferred unintentionally from the C_2 site to the C_{3i} site, since these sites are only about 3Å from each other, and this consequently induces a resonant energy transfer arising from a dipole-dipole interaction or wave function overlapping. We estimated this energy transfer time from the lifetime and the excitation power dependence of the PL spectra.

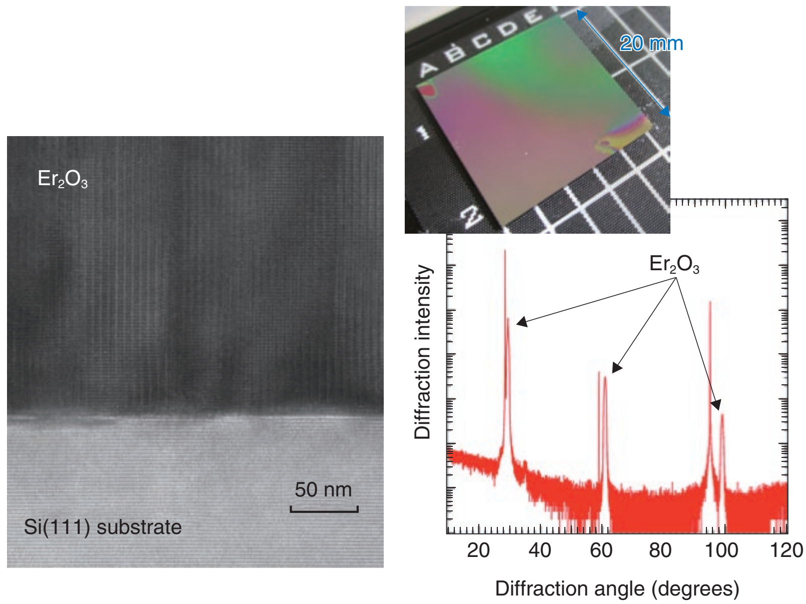


Fig. 3. Epitaxial Er_2O_3 thin films.

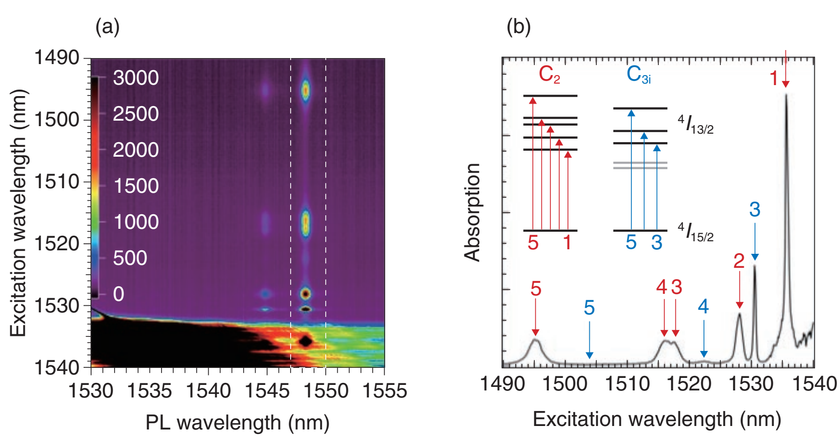


Fig. 4. Absorption and emission characteristics of energy levels in Er_2O_3.

As a result, we proved for the first time that the energy transfer is about 100 times faster (about 2 μs) than the relaxation between the excited and ground states.

The energy transfer is inconvenient for a quantum information manipulation platform, because the electron carrying the quantum information escapes to irrelevant states, and the manipulation time is limited to the energy transfer time. However, in numerical simulations using the Er_2O_3 parameters, we obtained primitive results showing that the obtained energy transfer times are sufficiently long compared with the time required to complete the coherent population transfer operation in Er_2O_3 crystals (less than several tens of nanoseconds). Therefore, we believe that the energy transfer has no effect on the quantum information manipulation.

5. Outlook

This article described the growth and optical characteristics of epitaxial Er_2O_3 thin film, which is a promising material as a platform for quantum information manipulation. We recently succeeded in controlling the distance between Er ions without any energy transfer—that is, with the suppression of the Er-Er interaction. This also led to the further suppression of energy fluctuation in the quantum state and an increased electron transition decay time. In addition, we are investigating the coherence time and spin state of the Er intra-4*f* orbital. Our goal is to achieve quantum information manipulation with a solid material based on Er_2O_3 crystals that can operate with telecom-band photons.

This work was a collaboration between NTT Basic Research Laboratories and Hokkaido University.

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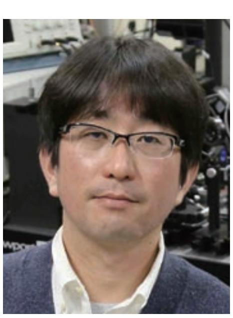

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Investigating the Properties of Glasses Using High Resolution Spectroscopy of Er^{3+} Ions

Daisuke Hashimoto and Kaoru Shimizu

Abstract

We have been investigating hyperfine sublevels of $^{167}Er^{3+}$ ions doped in a silicate glass fiber with the objective of demonstrating quantum memory in the 1.5-μm telecommunication band. Memory time is determined by the stability of hyperfine sublevels (the lifetime) of $^{167}Er^{3+}$ ions, so it is therefore necessary to clarify the lifetime properties. This article describes (i) the anomalous temperature dependence of the lifetime that was unexpectedly discovered in the lifetime measurements and (ii) the physical properties of glass that resulted in the anomalous phenomenon.

Keywords: $^{167}Er^{3+}$ ions, hyperfine sublevels, Boson peak mode

1. Introduction

The hyperfine sublevel (hfs) properties of rare-earth (RE) ions doped in crystal have been studied intensively because RE-doped crystals are expected to be a promising material for solid-state quantum memories [1]. The memory time depends on the lifetime t_1 and phase relaxation time t_2 of hfs, and therefore, a systematic study was done to extend t_1 and t_2 to approximately seconds.

NTT Basic Research Laboratories has also been studying an Er^{3+}-doped material in order to develop a quantum memory. The hyperfine sublevels of $^{167}Er^{3+}$ ions doped in a silicate glass fiber are one of the key properties to achieve this. There are various reasons for this, including: (i) Er^{3+} ions have an optical transition line ($^4I_{15/2} \leftrightarrow {}^4I_{13/2}$), (ii) the interaction between the Er^{3+} ions and light is enhanced because of the small mode field diameter (on the micrometer order), and (iii) the inhomogeneous broadening of the optical transition can provide a broadband quantum memory.

We succeeded in measuring the t_1 value of the hfs at 2.5–30 K using a spectroscopy method we developed, and we observed an anomalous temperature dependence whereby t_1 becomes shorter as the temperature decreases from 30 K to 4 K [2]. This t_1 behavior is completely different from the generally accepted view in the case of a crystalline host, where t_1 becomes longer as the temperature decreases. We can consider that the glass host structure surrounding the $^{167}Er^{3+}$ ions results in the anomalous temperature dependence. To describe this anomalous phenomenon, we examined the role of the Boson peak mode in the t_1 behavior, which is a lattice vibration characteristic of glasses.

2. Er^{3+} ions doped in a silicate glass fiber

A schematic energy-level diagram of Er^{3+} ions doped in a silicate glass fiber is shown in **Fig. 1**. The local electric field from the atoms and ions constituting the glass causes energy-level splitting to 8 levels for the ground state ($^4I_{15/2}$) and 7 levels for the excited state ($^4I_{13/2}$). The splitting energy is around several hundred GHz to 1 THz.

Of the many Er isotopes, only ^{167}Er has a nuclear spin of 7/2 with an abundance ratio of 23%. The energy levels of $^{167}Er^{3+}$ ions exhibit further splitting to 16 hyperfine sublevels with a splitting energy of around 1 GHz. This occurs because of the interaction between the electrons and the magnetic field from the nuclear spin.

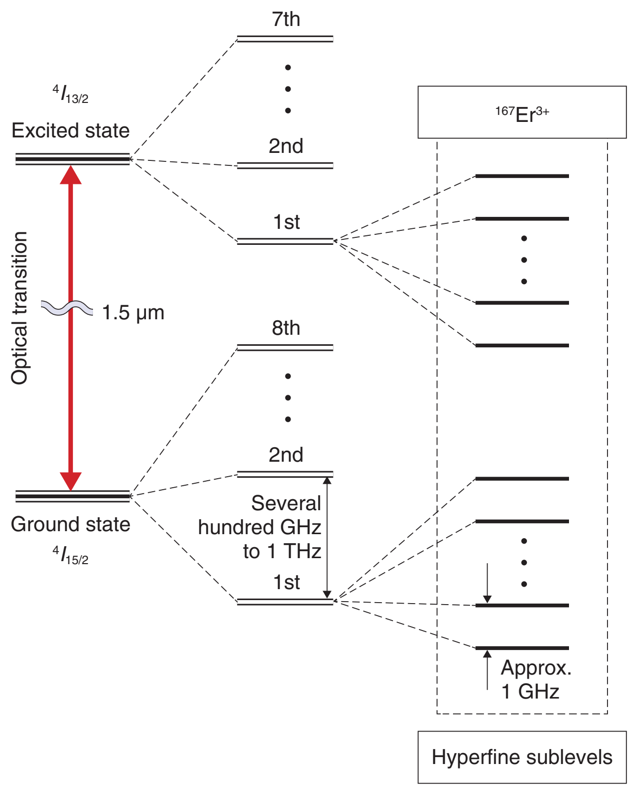


Fig. 1. Schematic energy-level diagram of Er^{3+} ions doped in a silicate glass fiber.

The optical properties of Er^{3+} ions doped in a silicate glass fiber have already been studied at the level of approximately 1 K [3]. Those studies revealed a homogeneous linewidth of about 10 MHz at 1 K, an inhomogeneous linewidth of about 1 THz, and an optical transition lifetime T_1 of 10 ms, which is independent of temperature and equivalent to that of the case with a crystalline host. By contrast, the properties of the hfs have not yet been clarified. They exhibit large inhomogeneous broadening and may have a very short lifetime t_1 compared with the crystalline host case. Consequently, it is difficult to measure these values with conventional techniques such as spectral hole burning and photon echo.

3. Measurement of lifetime t_1

We employed a technique that we call transient saturation spectroscopy to measure t_1. Our method consists of two steps: (i) the preparation for an initial state by absorption saturation and (ii) the transition to a final state by relaxation after step (i). In step (i), we saturate the absorption of the optical transition of certain Er^{3+} ions that are resonant with an intense and sufficiently long pump light pulse. This process makes it possible to selectively excite particular $^{167}Er^{3+}$ ions with an optical transition wavelength of around 1.53 μm. In a steady state, the electronic populations are distributed to the eight different hfs in the ground and excited states, as shown in Fig. 1. In step (ii), we immediately launch a weak probe light pulse with the same frequency as that of the pump light after turning off the pump light pulse. Because the intensity of the probe light pulse is sufficiently lower than that of the pump light pulse, the electronic population of each level relaxes to the ground levels with the optical transition lifetime T_1 and hfs lifetime t_1. Then, we can observe the transient increase in the absorption of the probe light pulse accompanied by the population relaxation, which in turn enables us to estimate T_1 and t_1 by measuring the decrease in the transmitted intensity of the probe light pulse.

The experimental setup is shown in **Fig. 2(a)**. We used a wavelength-tunable laser diode with its wavelength set at 1533.2 nm. The output was divided into pump and probe lights that were then pulsed by acousto-optic modulators (AOMs), where the duration and temporal position of the two pulses were controlled. The two pulses were launched into a 4.5-m Er^{3+}-doped silicate glass fiber cooled in a cryostat system from opposite ends. The transmitted probe pulses were detected with a photodetector. The input powers of the pump and probe pulses were −6 dBm and −27 dBm, respectively. The probe pulse was launched immediately after the pump pulse had been turned off (**Fig. 2(b)**). The duration of each light pulse was 45 ms, and the operation period was 100 ms.

4. Lifetime properties of hyperfine sublevels of $^{167}Er^{3+}$ ions

The temporal change in the transmitted intensity of the probe pulse is shown in **Fig. 3(a)**, where the temperature of the Er^{3+}-doped silicate glass fiber was 4 K. We can clearly observe the intensity reduction with the two time constants of T_1 and t_1. We can estimate the t_1 value at 3.1 ms at 4 K from the results.

The measured population relaxation rate β $(= (3t_1)^{-1})$ is shown in **Fig. 3(b)** with respect to the temperature from 2.5 K to 30 K. The β value exhibited a nearly constant value of approximately $2\pi \times 7.5$ Hz from 30 K to 20 K. Then it increased from $2\pi \times 8.6$ Hz to $2\pi \times 17.2$ Hz with respect to the decrease in temperature from 20 K to 4 K. In the temperature region from 30 K to 4 K, we observed the anomalous

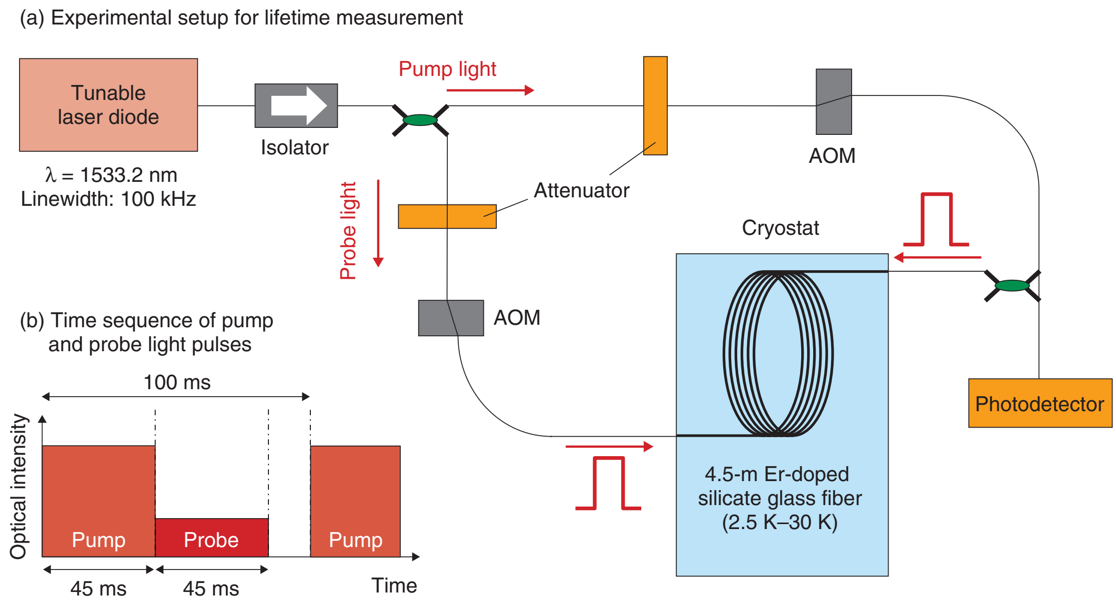
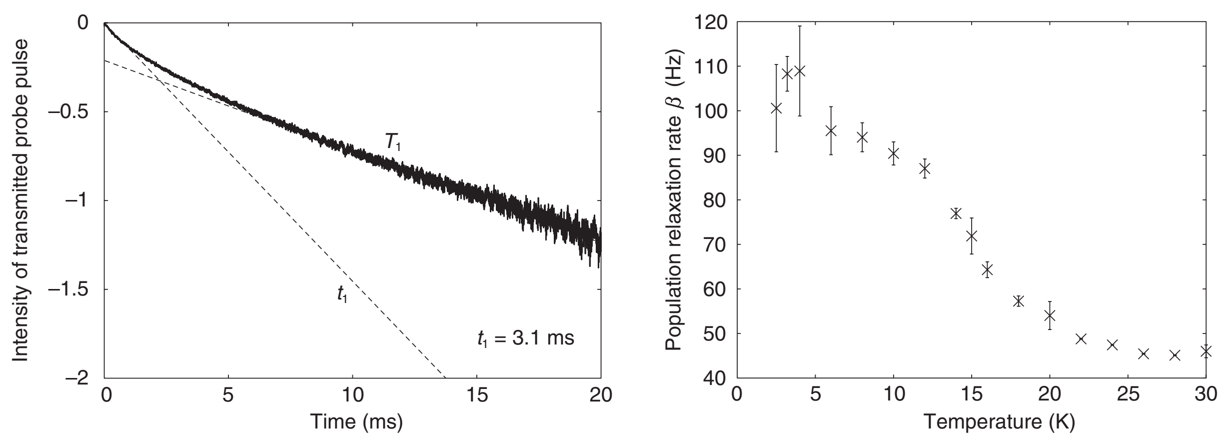


Fig. 2. Lifetime measurement.



(a) Temporal change in transmitted intensity of probe pulse at 4 K.

(b) Temperature dependence of population relaxation rate $\beta = (3t_1)^{-1}$

Fig. 3. Lifetime properties of hyperfine sublevels of $^{167}Er^{3+}$ ions.

temperature dependence in which the β value increased even though the temperature decreased. This observation is in direct conflict with the usual view that thermal suppression stabilizes any quantum state. In fact, with Eu^{3+} ions doped in the crystalline host (Eu^{3+}:Y_2SiO_5), a temperature decrease from 18 K to 4 K suppresses the population relaxation of hfs from $2\pi \times 0.1$ Hz to $2\pi \times 10^{-6}$ Hz. This comparison with the crystalline host case suggests that the anomalous temperature dependence of β can be attributed to the noncrystalline properties of a silica glass host. However, the β value decreased from $2\pi \times 17.2$ Hz to $2\pi \times 16.0$ Hz with respect to the further decrease in temperature from 4 K to 2.5 K. This behavior is in line with the usual view.

NTT Basic Research Laboratories unexpectedly found the anomalous temperature dependence of the hfs population relaxation rate β described above. We

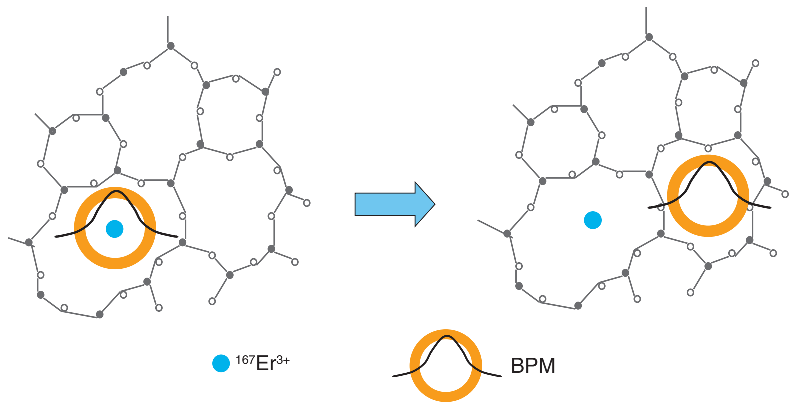


Fig. 4. Illustration showing hopping of BPM.

explain the physical aspect of this phenomenon in the next section.

5. Boson peak mode (BPM) in a glass

Two features that are common in glasses are an absence of translational symmetry and a disordered structure. The disordered structure results in a localized lattice vibration (phonon) mode if its wavelength is comparable to the disorder. This suggests that various low-energy vibration modes are present other than the propagation mode. In fact, it has been known for half a century that the lattice vibration in glasses shows a peak density of states (DOS) when the vibration frequency is 1 THz and the linewidth is approximately 2 THz, which is called a Boson peak. However, there is still no consensus on the origin of the lattice vibration.

Several experiments have been done in the last decade using inelastic scattering of neutrons and optical Raman scattering. These experiments have gradually clarified the characteristics of the lattice vibration mode, referred to as a Boson peak mode (BPM), which may result in a Boson peak. These experiments indicated that the BPM in a silicate glass was a strongly localized mode and was relevant to the torsional motion of the SiO_4 tetrahedron, which is a solid structure unit of the silicate glass. Moreover, they suggested another quite interesting feature in which the BPM that is localized at one site hops to other sites with the assistance of propagating acoustic phonons. Because the acoustic phonons increase proportionally with temperature T, the hopping probability is also proportional to T.

6. Relaxation induced by BPM in hfs of $^{167}Er^{3+}$ ions

We calculated the hfs population relaxation rate β for the interaction with the BPM in order to explain the obtained temperature dependence profile of β. Because the BPM in the neighbor of an Er^{3+} ion hops to another site at a certain time (**Fig. 4**), we can consider that the interaction time with the BPM is determined by the lifetime that the BPM stays at a particular site. When this lifetime increases with respect to the decrease in temperature, the long interaction with BPM promotes the relaxation of hfs of the $^{167}Er^{3+}$ ions.

The profiles for the experimental and theoretical results are shown in **Fig. 5**. The profile for the theoretical results shows good agreement with that for the experimental results in the temperature region from 8 K to 30 K. This suggests that a picture of the BPM localization and hopping with the assistance of propagating phonons has been successfully obtained, which enables us to describe our experiments. The quantitative discrepancy for the temperature range of 2.5–8 K seems to be attributed to (i) underestimation of the DOS of BPM and (ii) other localized vibration modes. Nevertheless, we have succeeded in qualitatively showing the peak of the β profile.

7. Future work

In the temperature region lower than 2.5 K, the experimental and theoretical results show a significant decrease in β. We therefore intend to measure the lifetime t_1 in that region and to confirm the long lifetime. After that, we will conduct quantum memory experiments.

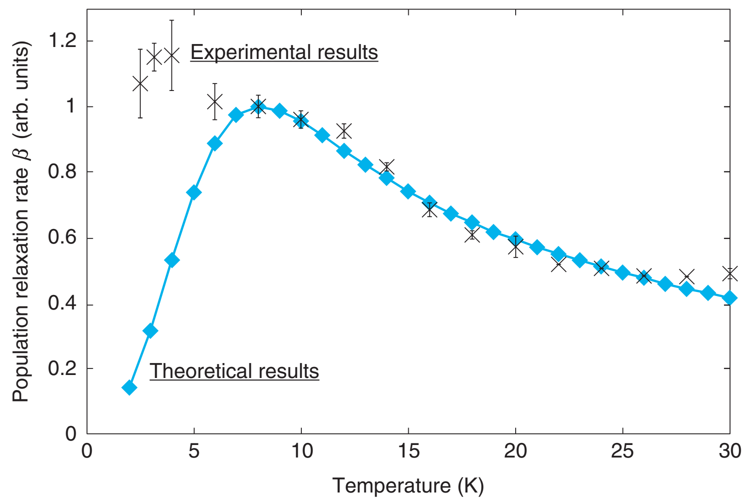


Fig. 5. Profiles for experimental and theoretical results.

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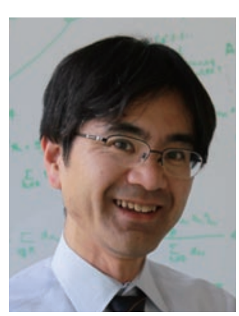

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A Bose-Einstein Condensate Achieved on a Persistent-supercurrent Atom Chip

Tetsuya Mukai and Hiromitsu Imai

Abstract

A persistent-supercurrent atom chip is a quantum device designed with a view to transcending the limits of conventional technologies by employing some of the significant properties of quantum mechanics. We have applied this novel technique to achieve an atomic gas in a macroscopic quantum state in the vicinity of a solid-state surface. In this article, we review a technique for making an extremely stable Bose-Einstein condensate above a chip surface and describe our attempts to overcome several unpredicted problems introduced by superconductivity.

Keywords: atom chip, superconductor, quantum devices

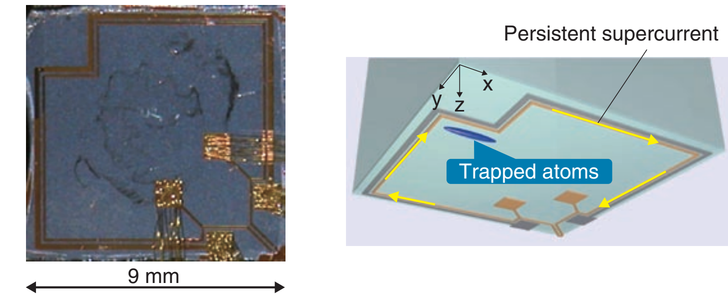
1. Introduction

Quantum mechanics, the branch of physics dealing with the small-scale world of atoms and photons, provides peculiar outcomes that are counterintuitive to those familiar with the macroscopic world. A probabilistic state is a good example; in addition to definite states of 0 or 1, quantum mechanics allows the existence of probabilistic states with superpositions of 0 and 1. Such non-intuitive quantum properties are strongly expected to be a key resource for realizing ultra-high-speed calculations and ultimately secure quantum cryptography. The realization of these transcendent technologies requires the development of quantum devices, e.g., quantum memories and gates, with which we can store and operate quantum states. Quantum device research on photons, ions, semiconductors, and superconductors is underway throughout the world out of both purely scientific interest and the desire to surpass classical technologies. We are focusing our research on ultra-cold atoms with which we can potentially realize scalable quantum devices.

In 2007 we detailed our prospects for developing atomic quantum devices by introducing a persistent-supercurrent atom chip [1]. In that article, we mentioned techniques for decelerating the velocity of atoms from about 300 m/s to 0 m/s with lasers, and for holding the atoms in a stable magnetic potential generated by a persistent supercurrent. In this article, we describe the further progress that we have made with the persistent-supercurrent atom chip. We have succeeded in achieving atomic gas in a macroscopic quantum state, i.e., a Bose-Einstein condensate (BEC), by taking advantage of the stable potential near the surface of a chip. Achieving a BEC was not straightforward; we encountered a lot of strange superconductor behavior and struggled, ultimately successfully, to find the correct route.

An atomic BEC is an isolated pure state with many controllable parameters, and it is attracting considerable interest in the field of science. Our recent achievement of a stable BEC on a chip is regarded as a technical breakthrough that is paving the way for BEC applications in engineering. The initialization of quantum devices is a promising target of such applications. An atomic BEC is analogous to lasers in electromagnetic waves; it exhibits good coherence in de Broglie waves, and a single coherent state constituted with a large number of atoms is useful for quantum memory and gate operations.

Although our research still requires further



(a) Photo image of persistent-supercurrent atom chip

(b) Schematic image of trapped atoms on chip

Fig. 1. Persistent-supercurrent atom chip.

improvement, we summarize our progress here and explain the novel techniques we have achieved so far along with the efforts we have made to overcome unpredictable problems encountered during the development.

2. Peculiar behavior of superconducting atom chips

When we succeeded in trapping atoms with our persistent-supercurrent atom chips (**Fig. 1**) [2], we believed that the trap had to be extremely stable even in the vicinity of a solid-state surface because spin-flip loss is suppressed. To evaluate the performance of our superconducting atom chip, we examined its trapping stability and found that the trap lifetime was ten times that achieved with conventional techniques [3]. This result was clearly an improvement; however, it did not satisfy us because the lifetime was much shorter than we had expected. According to our theoretical calculations, the trapping lifetime of superconducting atom chips should be more than 10,000 times longer than that of normal conducting atom chips. In addition to the unexpectedly short lifetime, we also encountered unreasonable fluctuations in the lifetime measurements. These strange results were caused by an interesting property of superconducting materials, which we came to understand later, as described below.

Type II superconductors, with which we can drive a relatively large current and achieve strong confinement in a magnetic potential, are advantageous for use in atom chip experiments. As is well known, magnetic fluxes penetrate and remain in the body of type II superconductors. The flux penetration condition strongly depends on the intensity of the magnetic field applied from outside the superconductor, but the critical field value is about ten times larger than the value that we usually use in cold atom experiments. For this reason we disregarded the influence of magnetic-flux penetration into our type II superconducting circuit on a chip. As we found out later, the flux penetration criterion also depends on the thickness of the superconductor. With a thin film superconductor, the critical field for the flux penetration becomes much smaller than that of a bulk superconductor. Moreover, the penetrated magnetic fluxes change their patterns from homogeneous to dendritic configurations depending on the temperature and the magnetic field around the superconducting film. We encountered these peculiar and interesting phenomena when measuring atomic clouds with our superconducting atom chips [4]. At first we thought we might have found an unknown physical property. However, the phenomenon, which is called *dendritic flux avalanche*, had been observed only a few years before with a completely different technique.

Once the mechanism of the problem was clarified, it was not that difficult to come up with tactics to overcome the problem. Controlling the chip temperature was the key to achieving stable operation of superconducting atom chips. To give the superconductor zero resistivity, we have to cool the chip below a critical temperature T_c. To keep the penetrated magnetic fluxes stable, the chip temperature should be higher than another critical temperature T_d, at which the penetrated magnetic fluxes change to a dendritic pattern. By controlling the chip temperature so that it was between T_d and T_c, we succeeded in achieving an extremely stable magnetic potential with our superconducting atom chip.

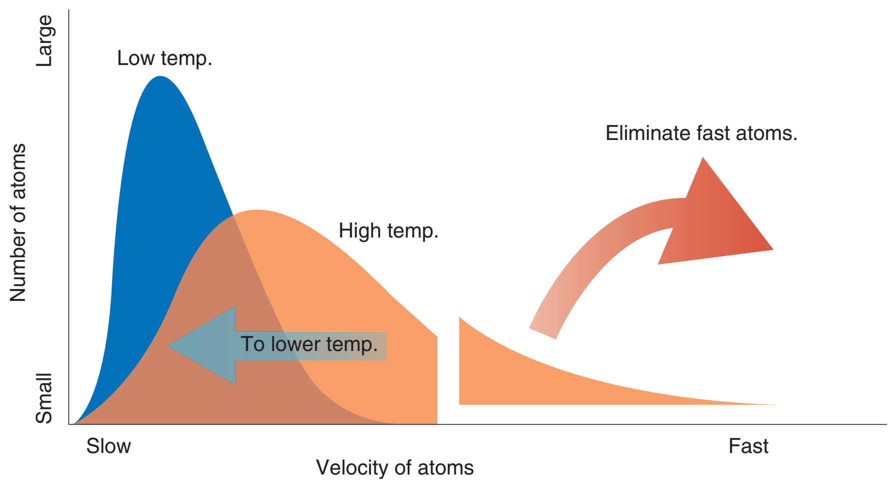


Fig. 2. Schematic image of evaporative cooling.

3. Evaporative cooling with a superconducting closed loop circuit

The first step in making a BEC is to create a stable atomic cloud; the next step is to further reduce the atomic cloud temperature through evaporative cooling. The mechanism of evaporative cooling is easily understood with the help of the intuitive image shown in **Fig. 2**. First, energetic atoms are removed from the atomic cloud, and the remaining atoms then start to thermalize into an equilibrium state at a lower temperature through the atom interaction. In this process, a radio-frequency (RF) magnetic field is used in order to eliminate high-energy atoms from the atomic cloud through the use of resonant action. In atom chip experiments, the RF magnetic field is usually generated by an alternating current (AC) on a chip circuit. For the first trial in our experiment, we employed the same technique and introduced an AC into our chip circuit to generate an RF magnetic field. The result was poor; both the high-energy atoms and all the other atoms escaped from the trapping potential in a short period. As is usual when developing a new technology, unpredicted problems can be introduced by employing an old method; the combination of our novel superconducting circuit and a conventional AC on a chip circuit resulted in a problem arising from the unwanted behavior of the trapping potential.

With a superconducting closed loop circuit, the total magnetic flux or fluxoid (the sum of the magnetic field applied from outside and the field generated by the circuit current) inside the closed loop circuit is preserved, which is called fluxoid conservation. By properly applying this natural law, we can drive a persistent current into a closed loop circuit without connecting a power supply to the chip circuit. This is a key advantage of our technique because it suppresses the electromagnetic noise arriving from the environment through conducting wires. However, the natural principle also means that a current in a closed loop circuit is sensitive to a magnetic field penetrating through the circuit itself. In our experiment, an RF magnetic field generated by an AC on a chip penetrated the closed loop circuit and modified the persistent current. The modulated persistent current vibrated the trapping potential and resulted in atoms being lost from the potential.

Finally, we came to understand that the RF magnetic field for evaporation should be applied parallel to the chip surface to avoid field penetration of the closed-loop circuit. To realize this configuration, we attached an independent single-loop RF coil perpendicularly to the chip circuit, and succeeded in evaporatively cooling the atomic cloud to form a BEC by removing only the energetic atoms from the trapping potential [5].

4. BEC measurements

We investigated the BEC on a persistent-supercurrent atom chip with a time-of-flight imaging technique. First, an atomic cloud was released from the trapping potential, and then an absorption image was captured as a shadow of the atomic cloud, which was expanding depending on the initial temperature in the trap. Typical images obtained before and after the

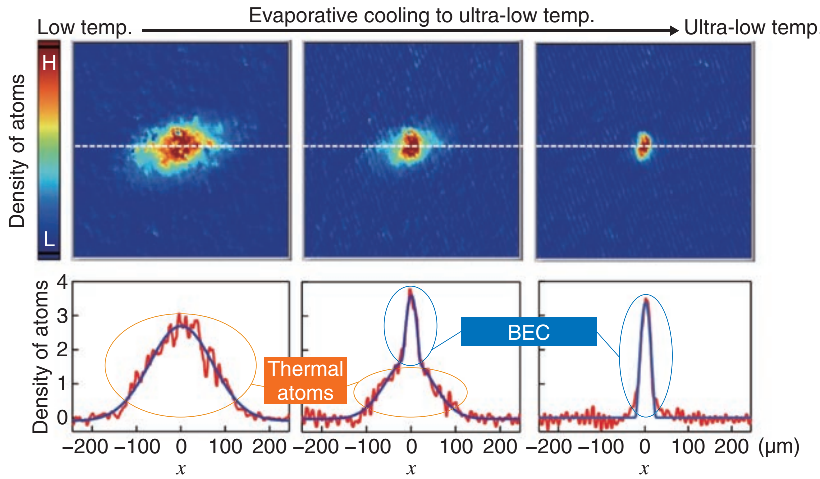


Fig. 3. Time-of-flight images at instance of BEC transition.

BEC transition are shown in **Fig. 3**. The left image shows a relatively large distribution of the atomic cloud, which suggests a high temperature, whereas the right image shows a small distribution, suggesting a low temperature. In the center image, the created BEC is observed as a higher density at the center of the atomic cloud. The image on the right shows that almost all of the 100,000 atoms are condensed into the potential ground state. The change in the atomic-cloud shape from a large horizontal configuration (left) to a small longitudinal one (right) is also apparent in this figure. This configuration change also proves that we were successful in achieving a BEC.

5. Future prospects

We have achieved a BEC in the extremely stable potential of a persistent-supercurrent atom chip. The long coherence time for preserving fragile quantum states is outstanding compared with conventional technology. If we assume single atoms as single qubits, a BEC composed of 100,000 atoms is equivalent to a single package of 100,000 initialized qubits. The next step is to develop a technique for separating a BEC into several atomic clouds or single atoms and for controlling each atomic cloud independently. If we succeed in developing a technique such as that shown in **Fig. 4**, we will come very close to realizing atomic quantum devices.

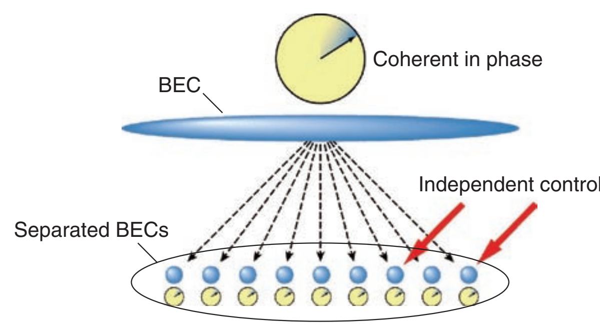


Fig. 4. Illustration of BEC application.

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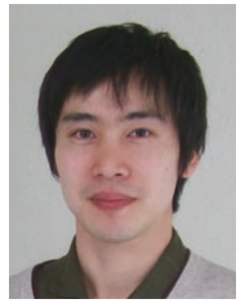

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"hitoe"—A Wearable Sensor Developed through Cross-industrial Collaboration

Kazuhiko Takagahara, Kazuyoshi Ono, Naoki Oda, and Takashi Teshigawara

Abstract

NTT succeeded in developing a novel composite material consisting of a flexible conductive fiber fabricated by coating fiber material such as silk with a conductive polymer (poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate): PEDOT-PSS). A press release on this development was issued in February 2013. Then, in January 2014, after forming a tie-up with NTT DOCOMO to spearhead the development of related services, NTT jointly announced with Toray Industries, Inc. and NTT DOCOMO the development of this composite conductive fiber material under the brand name "hitoe." This article introduces the technology behind the hitoe material and discusses future scenarios in which the biomedical signals measured by hitoe should prove useful.

Keywords: wearable sensor, electrocardiogram, biomedical signal monitoring

1. Introduction

"hitoe" is a functional material capable of measuring biomedical signals to obtain, for example, a person's electrocardiogram or electromyogram. This material was developed by applying NTT-developed conductive fiber technology, in which fiber material is coated with a conductive polymer (poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate): PEDOT-PSS), to the cutting-edge nanofiber material developed by Toray Industries, Inc. (Toray) (**Fig. 1**). Compared with conventional fiber material (fiber diameter: about 10 µm) used in ordinary clothing, nanofiber (fiber diameter: about 0.7 µm) improves adhesion to the skin, thereby facilitating stable measurement of biomedical signals. In addition, high conductivity and durability have been obtained in hitoe material by filling the gap between nanofibers with conductive polymer using Toray's advanced high-order processing technology.

The hitoe material has been embedded in an inner T-shirt to make it easy to wear on the human body. This has resulted in the development of a wearable sensor that can record a person's electrocardiogram (**Fig. 2**). The base material of this T-shirt makes use of PROGRESKIN, a material whose compressive force on the human body fluctuates very little even when the shirt is stretched. This material provides a good fit by accommodating differences in body types, and it conforms well to physical movements. In addition, the parts of the T-shirt embedded with the hitoe material have a material configuration that has high moisture retention, which reduces contact impedance with the human body.

The above features make it possible to detect a person's biomedical signals in a comfortable and stable manner in a variety of everyday scenarios simply by having the person wear this newly developed T-shirt.

2. Examples of measuring everyday biomedical signals using hitoe

The hitoe material is a cloth-based electrode

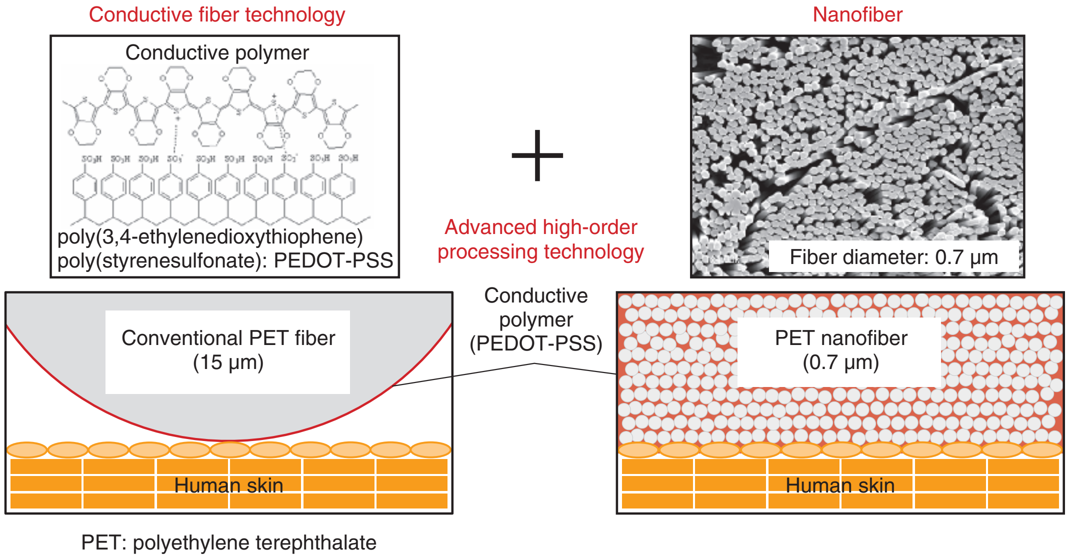

Fig. 1. Elemental technologies of hitoe.

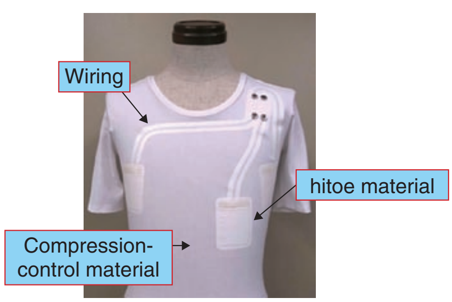

Fig. 2. hitoe-embedded inner T-shirt.

material with superior elasticity and breathability. When embedded in an inner T-shirt that is worn by a user, it can be used to easily obtain long-term recordings of the user's heart rate and electrocardiogram in a variety of everyday scenarios.

Changes in a person's mental state can be visualized by analyzing fluctuations in that person's heart rate over time. An example of heart rate fluctuation obtained within a business scenario is shown in **Fig. 3**. The horizontal and vertical axes represent time and heart rate, respectively. In the figure, periods A and C correspond to deskwork, while period B corresponds to a presentation made in front of a large number of people. As shown, the heart rate is higher, and heart rate turbulence (variation) is lower in period B compared with periods A and C. This response demonstrates that the sympathetic nervous system holds a dominant position in the autonomic nervous system that controls a person's heart pulsations, and that the person in question was under considerable stress in period B. Another example of a technique for visualizing changes in heart rate is shown in **Fig. 4**. Five minutes' worth of heart rate fluctuation is extracted from periods A and B and shown as a Poincaré plot. Given an electrocardiogram waveform, a Poincaré plot represents the interval between one heartbeat's R wave to the next R wave (R-R interval) at a certain time on the horizontal axis and the immediately subsequent R-R interval on the vertical axis. The results of such a plot become concentrated as heart rate turbulence becomes smaller (stress state) and, conversely, become dispersed during a period of relaxation. In this way, an inner T-shirt embedded with hitoe material can be used to measure heart rate intervals with high accuracy over the long term based on the person's electrocardiogram waveform, and the obtained results can be applied in an analysis of that person's mental state.

This newly developed inner T-shirt embedded with hitoe material is fabricated using Toray's compression-control material as the base material for the shirt itself. This enables long-term recording of a person's heart rate fluctuation or electrocardiogram even for lifestyle scenarios that include intense physical movements, as in sports.

The results of measuring an athlete's heart rate

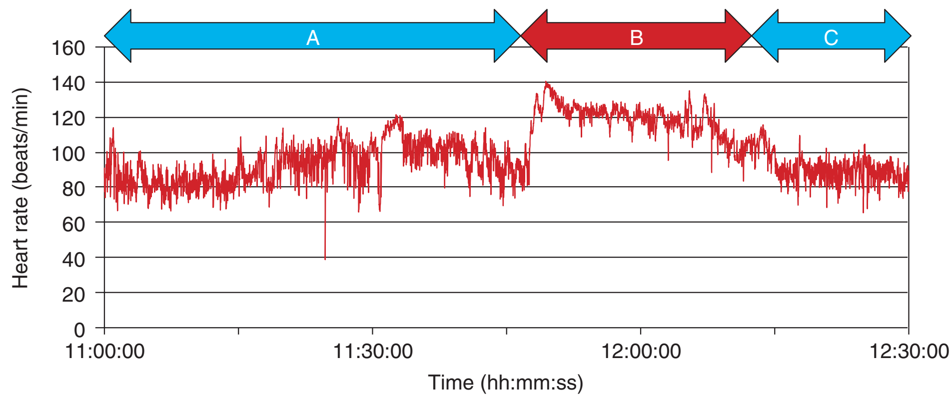

Fig. 3. Fluctuation in heart rate obtained in a business scenario.

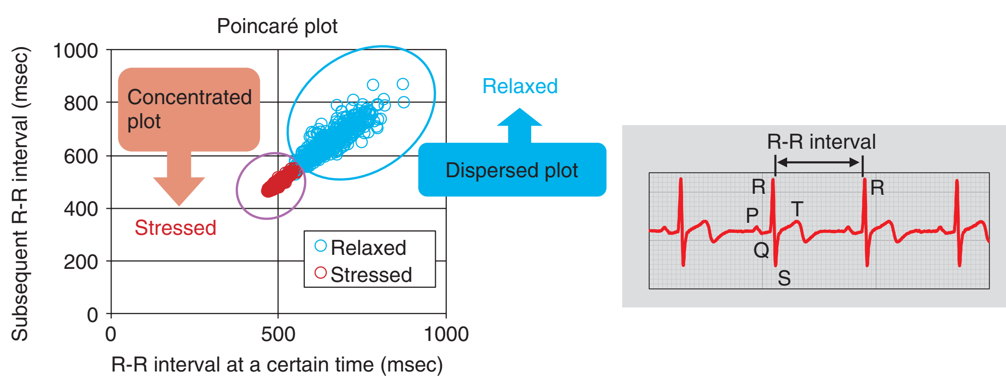

Fig. 4. Poincaré plot of heart rate variability.

fluctuation during a badminton doubles match are shown in **Fig. 5(a)**. These results demonstrate that heart rate fluctuation can be captured throughout a period of about 40 minutes even during a match involving strenuous movement in the upper body. The heart rate fluctuations of an experienced player and a beginner during the match are compared in **Fig. 5(b)**. It can be seen here that the heart rates of both the experienced player and the beginner jumped during rallies. However, on entering an interval (break) between rallies, the heart rate of the experienced player immediately dropped, while that of the beginner maintained a high value. Such fluctuation in heart rate can be viewed as a useful index for determining the extent of exercise load and recovery. Accordingly, highly effective training and health management can be obtained by having users wear a hitoe-embedded inner T-shirt while their heart rate fluctuation is managed.

3. Electrocardiogram-waveform transmitter

An inner T-shirt embedded with hitoe material can obtain electrocardiogram waveforms in addition to heart rate fluctuation. Moreover, the electrocardiogram waveform can be transmitted to a smartphone via wireless means (Bluetooth) when the T-shirt is affixed with an electrocardiogram-waveform transmitter, as shown in **Fig. 6**. The electrode arrangement in this T-shirt can obtain a waveform similar to that of CC5 leads in a Holter monitor. In addition to sharp QRS waves, preceding and succeeding P and T waves can be cleanly measured and displayed.

4. Looking ahead

Looking forward, we aim to contribute to the expansion of the sports, health-management, and

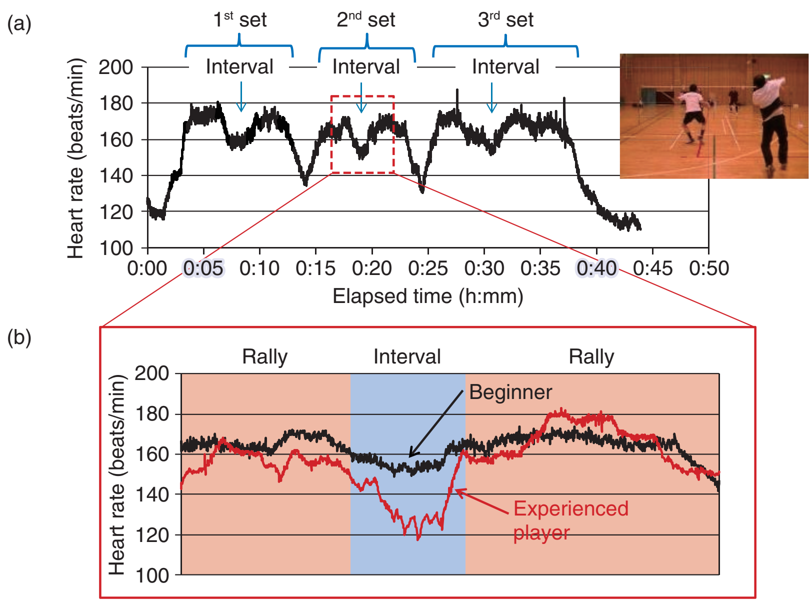

Fig. 5. Heart rate fluctuation during badminton doubles match.

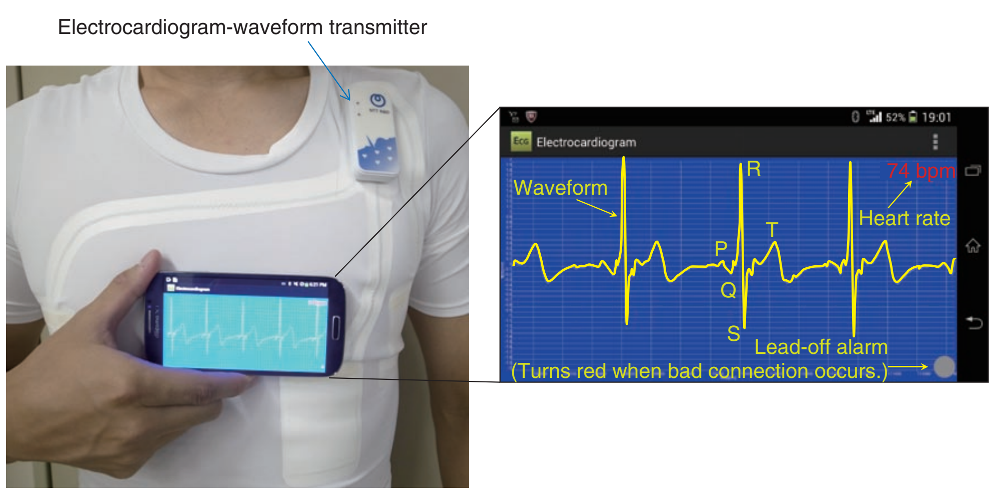

Fig. 6. Electrocardiogram measurement using smartphone.

medical care fields by creating innovative services based on our hitoe material. For example, we can envision the transmission of electrocardiogram-waveform data and other types of biomedical information to the Internet from smartphones and the use of cloud services and big data analysis in conjunction with health-support services offered by NTT DOCOMO.

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Standardization Efforts in IP Interconnect Specifications

Seiichi Sakaya, Kenjiro Arai, and Shunsuke Kanegae

Abstract

As the use of VoIP (voice-over-Internet protocol) telephone services continues to spread, it is becoming increasingly desirable to migrate the connections between communications carriers to IP technology (IP interconnection) rather than connecting them through the existing public switched telephone networks. We describe here the domestic and international trends in standardization of IP interconnection interfaces as well as the NTT initiatives in this area.

Keywords: IP interconnection, VoIP, standardization

1. Introduction

As Internet protocol (IP)-based communication services have spread on the Internet, the migration to providing voice-over-IP (VoIP) and other telephony services on IP networks has been rapidly advancing. For example, the Next Generation Network (NGN) is the basis for provision of telephony services such as *Hikari Denwa*; the FOMA mobile network is migrating telephone services to an IP-based circuit-switched core network [1]; and VoLTE (Voice-over-LTE (Long Term Evolution)) services were started in June 2014.

To enable users served by different carriers to talk with each other, the networks of each communications carrier need to be interconnected. With conventional VoIP services, each VoIP provider's network was generally connected to the existing public switched telephone network (PSTN), and connections between VoIP carriers were implemented through the PSTN.

However, as these IP-based telephone services have spread, and the possibility of migrating existing telephone networks from PSTN to IP-based technology has become a reality, it is becoming more desirable to migrate the interconnections between carriers to IP-based technology as well, rather than maintaining connections through the PSTN (**Fig. 1**).

2. VoIP standardization trends

Currently, the session initiation protocol (SIP) is used as a protocol for VoIP session control (connecting and disconnecting with the other party). The basic specifications for SIP are standardized in RFC (Request for Comments) 3261 developed by the Internet Engineering Task Force (IETF), an organization that develops technical standards for the Internet. In addition to the basic specifications of RFC 3261, many extensions to the basic SIP have also been developed. An RFC guide created by IETF that is related to SIP (RFC 5411: A Hitchhiker's Guide to the Session Initiation Protocol (SIP)), indicates that there were over 100 related RFCs as of 2009. For VoIP services, communications carriers need to select the technical specifications for the services they need to implement from among numerous RFCs, and then they need to decide various rules (standards) needed to operate the VoIP service such as the service architecture, security, and charging structure.

Accordingly, the standards and international specifications required by communications carriers to provide their services were deliberated and developed by standardization organizations including the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) and the 3rd Generation Partnership Project (3GPP), which was organized to promote standardization of 3rd generation and later mobile communications. Then, based on

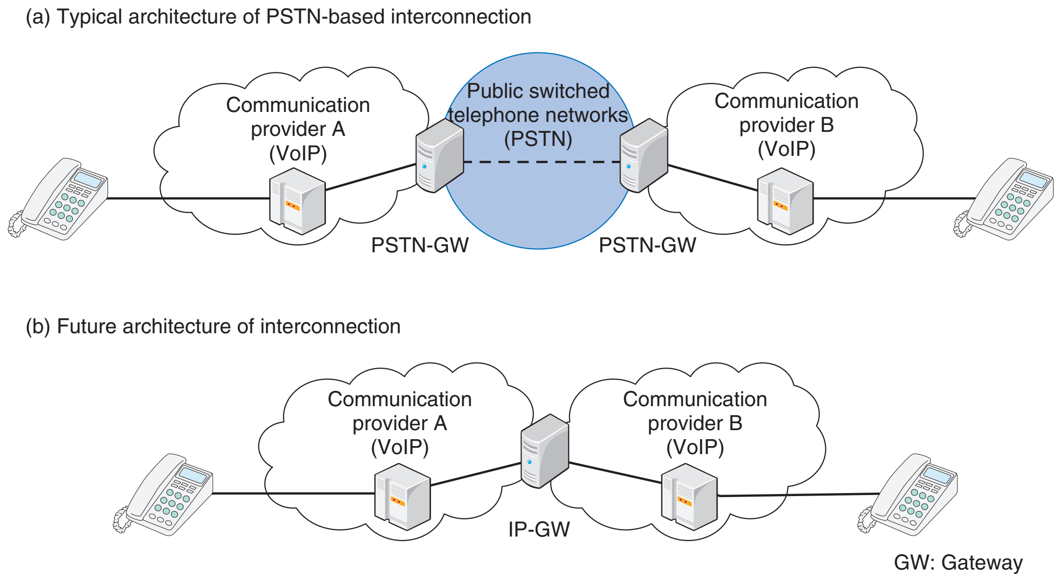

Fig. 1. Architecture of interconnection for VoIP services.

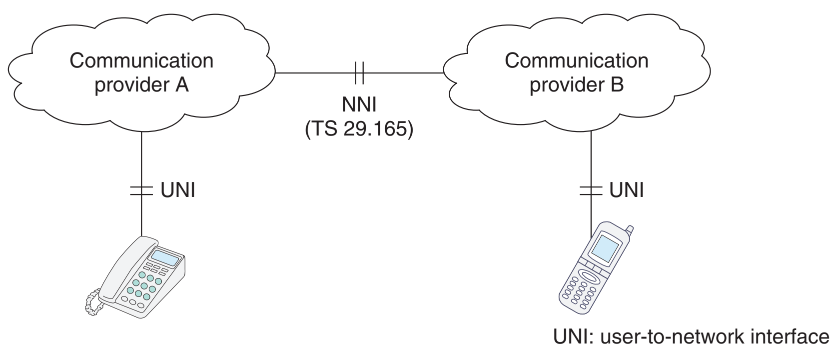

Fig. 2. Interconnection model in 3GPP Technical Specification (TS) 29.165.

these international specifications, domestic standards specific to each country (e.g., related to telephone number formats, additional services, and emergency services) are developed by regional standardization organizations in the respective countries. In Japan, the signaling specifications for VoIP services applied within Japan are standardized by the Telecommunication Technology Committee (TTC).

3. NTT initiatives for international standardization of IP interconnection

Our group is working on some initiatives for standardizing the interface between communications carriers, which is called the network-to-network interface (NNI), to enable future IP interconnection between carriers (**Fig. 2**).

The NNI specification for VoIP within Japan is JT-Q3401, which was created by the TTC in 2007. This consists of the specifications contained in ITU-T Q.3401—an NGN NNI recommendation—and the signaling specifications of TR-90.25 applied within Japan [2].

In international standardization, the 3GPP created a new NNI specification between the IP multimedia subsystem (IMS) networks in 2008, which is known as Technical Specification (TS) 29.165 (Inter-IMS Network-to-Network Interface). This 3GPP

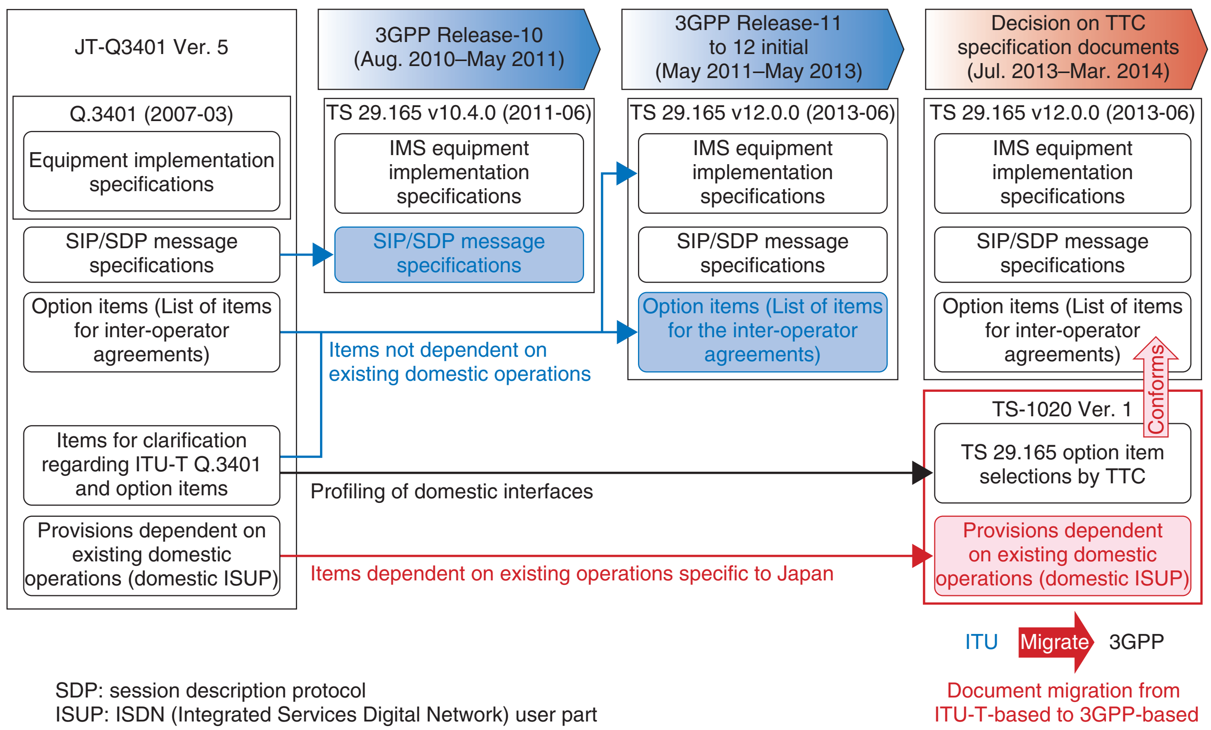

Fig. 3. Document composition for JT-Q3401, TS 29.165, and TS-1020.

specification has become the standard for implementing mobile networks. We expect that TS 29.165 will also be the basis for future domestic NNI specifications for IP interconnection, in which the interconnection between fixed and mobile networks needs to be addressed. However, the initial TS 29.165 was inadequate for use in Japan in some technical areas, so there was a need to reflect the signaling requirements to fulfill Japanese requirements in the international standard.

As such, our group began a differential analysis of the specifications in JT-Q3401 and TS 29.165. Then, we began work in fiscal year (FY) 2010 on incorporating all stipulations included in JT-Q3401 but not in TS 29.165, and that are not Japan-specific, into TS 29.165 in order to eliminate any differences. Then, in the three years leading to FY2013, we served as rapporteur in leading two work items containing over 300 contributions, and we were able to maximize the consistency between JT-Q3401 and TS 29.165.

4. NTT initiatives for standardization of IP interconnection within Japan

Telephony services on both mobile and fixed networks in Japan have been converted to IP; hence, there was increasing need to study the NNI specifications that will be the basis for IP interconnection between mobile and fixed networks. In FY2010, the Mobile/Fixed Network IP Interconnection Ad Hoc Study Group was established at TTC, by combining the signaling Working Group (WG), which primarily creates call control specifications, and three special mobile WGs (3GPP WG, 3GPP2 WG, and the mobile network management WG).

This ad hoc group shared information related to IP interconnection in areas of standardization and the activities of industry organizations, discussed the need for TTC standards of IP interconnection specifications, and clarified the scope of studies to be done. With the progress made in international standardization of NNI specifications, the TS-1020 NNI specification was published in FY2013, which conforms to TS 29.165 and includes the Japan-specific supplementary specification and clarifications. TS 29.165 was selected as the base document because it provides a framework equivalent to that in JT-Q3401 due to our activities at 3GPP. Considering future extensions to domestic specifications, it is appropriate to use the specification of 3GPP, where active discussions on IMS specifications are still taking place.

5. Overview of NNI technical specifications in Japan

TS-1020, created by TTC in 2013, specifies the basic NNI signaling requirements for IP interconnection between different communications carriers. Protocols and supported procedures conform to TS 29.165, and differences that cover circumstances in Japan are described in TS-1020. The following are examples of such items (**Fig. 3**).

- Supplementary specifications regarding telephone number formats and signaling requirements (e.g., interworking with existing circuit-switched networks).
- TTC selection of the option items specified as optional for application over the NNI in 3GPP.
- Supplementary information for maintenance and operating conditions and examples of call flow and message coding, which are useful in practical operation.

6. Future prospects

TS 29.165, which is the basis for TS-1020, is still being studied and updated at 3GPP. 3GPP studies progress in units called Releases, and when the study for TS-1020 began, the final version of TS 29.165 Release-12 was not yet completed, so the initial version was used as a reference. Therefore, the TTC specification was also created as a provisional technical specification. 3GPP TS 29.165 Release-12 is scheduled to be finalized in December 2014, so the TTC specification is also scheduled to advance to the next step after that, which is establishing it as a standard.

Also, as standardization advances at TTC, we plan to cover requests from operators covering issues such as the roaming interface (the NNI between the home network and visited networks), which is being requested by mobile operators, the signaling requirements for emergency services, which are required when inheriting the existing circuit-switched networks, and the signaling requirements related to number portability.

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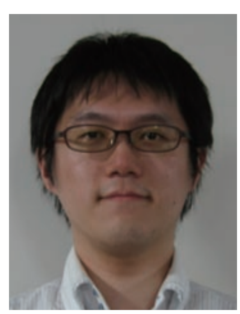

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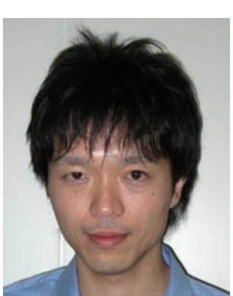

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External Awards

ICC 2014 Best Paper Award

Winner: Shohei Kamamura, Daisaku Shimazaki, Yoshihiko Uematsu, Koichi Genda, and Koji Sasayama, NTT Network Service Systems Laboratories
Date: June 14, 2014
Organization: Institute of Electrical and Electronics Engineers (IEEE)

For "Multi-staged Network Restoration from Massive Failures Considering Transition Risks".

In a scenario of restoration from massive failures, a network is repaired through multiple restoration stages because the availability of repair resources is limited. In a practical case, a network operator should assure the reachability of important traffic in transient stages, even as risks and/or operational overheads caused by stage transitions are suppressed. We discuss the novel problem of optimizing both traffic recovery ratio and transition risks caused by path switching operations. We formulate our problem as a linear programming problem and show that it obtains pareto-optimal solutions of traffic recovery versus transition risks. We also propose a heuristic algorithm for applying networks consisting of a few hundred nodes. The algorithm was able to produce sub-optimal solutions within a 4% difference from optimal solutions.

Published as: S. Kamamura, D. Shimazaki, Y. Uematsu, K. Genda, and K. Sasayama, "Multi-staged Network Restoration from Massive Failures Considering Transition Risks," Proc. of the IEEE International Conference on Communications (ICC) 2014, pp. 1314–1319, Sydney, Australia, June 2014.

Poster Presentation: Honorable Mention

Winner: Scinob Kuroki, Junji Watanabe, and Shin'ya Nishida, NTT Communication Science Laboratories
Date: June 26, 2014
Organization: EuroHaptics Society

For "Vibrotactile Frequency Discrimination Performance with Cross-channel Distractors".

Best Demonstration Award

Winner: Tomohiro Amemiya and Hiroaki Gomi, NTT Communication Science Laboratories
Date: June 26, 2014
Organization: EuroHaptics Society

For "Distinct Pseudo-attraction Force Sensation by a Thumb-sized Vibrator that Oscillates Asymmetrically".

Papers Published in Technical Journals and Conference Proceedings

Interference-aware Channel Segregation Based Dynamic Channel Assignment Using SNR-based Transmit Power Control

Y. Matsumura, K. Temma, K. Ishihara, B.A.H.S. Abeysekera, T. Kumagai, and F. Adachi

Proc. of ISPACS (International Symposium on Intelligent Signal Processing and Communications Systems) 2013, pp. 792–796, Naha, Japan, November 2013.

In any wireless network, the same channel must be reused at spatially separated access points or base stations and hence, the co-channel interference (CCI) limits the transmission quality. Therefore, it is very important to reuse the channels so as to minimize the CCIs. We recently proposed an interference-aware channel segregation based dynamic channel assignment (CS-DCA), which can form a stable channel reuse pattern in a distributed manner. The use of transmit power control (TPC) can avoid the excessive transmit power and hence, contributes to reducing the CCI. An interesting question is if the interference-aware CS-DCA can form a stable channel reuse pattern when TPC is used. In this paper, we give an answer to this question and show by computer simulation that a stable channel reuse pattern can be formed even if TPC is used and that the transmit power can be significantly reduced.

Wide-area Centralized Radio Resource Management for DCF-based Multi-hop Ad hoc Wireless Networks

S. Sampei, W. Jiang, S. Miyamoto, and N. Hayata

Proc. of ICNC (International Conference on Computing, Networking and Communications) 2014, pp. 710–715, Honolulu, HI, USA, February 2014.

This paper proposes a novel medium access control protocol that enables a wide area centralized radio resource management in a distributed coordination function (DCF)-based multi-hop wireless network.

A Novel Elastic Optical Path Network that Utilizes Bitrate-specific Anchored Frequency Slot Arrangement

Z. Shen, H. Hasegawa, K. Sato, T. Tanaka, and A. Hirano

Optics Express, Vol. 22, No. 3, pp. 3169–3179, February 2014.

We propose a novel elastic optical path network where each specific bitrate signal uses its own dedicated fixed grid and one edge of its frequency grid is anchored at a specific frequency. Numerical evaluations using various bitrate signal patterns and network topologies show that the network proposal can almost match the performance of conventional flexible grid networks, while greatly mitigating the hardware requirements: it allows the use of the tunable filters for the fixed grid systems.

Interoperability Enhancement for Realizing the Virtualization of Sensors for Smart Cities

H. Maeomichi and A. Tsutsui

Proc. of the IEEE World Forum on Internet of Things, pp. 365–366, Seoul, Korea, March 2014.

We discuss interoperability enhancement for sensor virtualization for smart cities. We propose a model of metadata and data conversion components for interoperability enhancement and introduce our research approach.

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100 Gbit/s DP-QPSK Transmission over a 32 km Legacy Multi-mode GI Fiber Using a Real-time Digital Coherent Transceiver

T. Hirooka, M. Nakazawa, T. Komukai, and T. Sakano

Proc. of OFC (Optical Fiber Communication Conference and Exposition) 2014, W2A.1, San Francisco, CA, USA, March 2014.

We demonstrate a 100-Gbit/s real-time digital coherent transmission over a 32-km GI-MMF (graded-index multimode fiber) with a 62.5-μm core diameter. The DSP enables the optical channel to be switched from SMF (single mode fiber) to GIF within 70 ms.

Network-controlled Channel Allocation Scheme for IEEE 802.11 Wireless LANs: Experimental and Simulation Study

B.A.H.S. Abeysekera, K. Ishihara, Y. Inoue, and M. Mizoguchi

Proc. of 2014 IEEE 79th Vehicular Technology Conference (VTC2014-Spring), Seoul, Korea, May 2014.

The increased density of wireless local area network (wireless LAN) access points (APs) based on the IEEE 802.11 standard has induced inter-cell interference that severely degrades system performance. In order to mitigate this issue, this paper proposes an efficient network-controlled channel allocation scheme that can be applied to a managed wireless LAN system with a central coordinator. On the basis of channel monitoring results obtained from APs and the data traffic amount at each AP, the central coordinator computes the quasi-optimal frequency channel of each AP in such a way that the given utility function is maximized. Numerous simulations and testbed experiments with UDP traffic flows show that the proposed scheme works well and improves the overall system throughput and fairness among throughput of APs even when there exist uncontrollable APs of other domains.

To Relive a Valuable Experience of the World at the Digital Museum

Y. Ikei, Y. Okuya, S. Shimabukuro, K. Abe, K. Hirota, and T. Amemiya

Proc. of HCI International 2014 (the 16th International Conference on Human-Computer Interaction), pp. 501–510, Heraklion, Crete, Greece, June 2014.

This paper describes a new concept of bodily experience that may be used in future museum exhibits. An ordinary museum exhibits objects so that they convey authenticity to visitors. However, these exhibits do not provide any interaction or a vivid context in which they existed. A virtual experience system which creates multisensory stimuli potentially presents the realistic state of valuable artificial objects in their original environments. We think the experience of objects in a particular space is another theme that future museums can present. A novel rendering technique of a virtual body of a visitor is introduced in such a way that multisensory displays impart the sensation of presence of an environment and objects of interest through a pseudo walking experience. This digital museum device will add a new experience of reliving a trip by walking around objects based on recorded data from real tourists.

First Step Guide for Building Cyber Threat Intelligence Team

H. Endoh and N. Inui

Proc. of the 26th Annual FIRST Conference, Boston, MA, USA, June 2014.

As cyber threats and attacks have evolved into sophisticated and goal-oriented attack scenarios, protection using conventional incident response methods has become increasingly difficult. The importance of Cyber Threat Intelligence is widely known by CSIRTs for the reason that although the detection phase is the first of the three basic incident response steps (detection, triage, response), recent attacks often go unnoticed for long periods of time, in some cases for years. On the other hand, there is a lack of know-how in building a Cyber Threat Intelligence Team. Through incident response services, the Cyber Defense Institute (CDI-CIRT) has gained knowledge on the importance of situational awareness, and the processes that follow in building a Cyber Threat intelligence team.

Multi View Layered GPDM for View Invariant Human 3D Pose Estimation from Single RGB Camera Input

A. Matsumoto, D. Mikami, X. Wu, H. Kawamura, and A. Kojima

IEICE Transactions on Information and Systems (Japanese Edition), Vol. J97-D, No. 7, pp. 1189–1201, July 2014.

We proposed a view-invariant 3D human pose estimation method from a monocular camera. Our method enables simultaneous estimation of 3D poses and viewpoints. In pre-learning, this method generates 2D pose data corresponding to the virtual multiple views from 3D pose data; then it builds view-prior models in the low-dimensional space from 2D position data of each point of view. In the pose estimation, it only provides the initial viewpoint and dynamically chooses a view-prior model. This is what makes simultaneous estimation of the 3D pose and viewpoint data possible. In this paper, we describe experiments on motion category of "walking." It was confirmed that even when the relative unknown positional relationship between the person and the camera moves, stable pose estimation results as compared with the conventional method are obtained.

Plug-and-play Optical Interconnection Using Digital Coherent Technology for Resilient Network Based on Movable and Deployable ICT Resource Unit

T. Komukai, T. Sakano, H. Kubota, T. Hirooka, and M. Nakazawa

IEICE Transactions on Communications, Vol. E97-B, No. 7, pp. 1334–1341, July 2014.

In response to the Great East Japan Earthquake in March 2011, the authors have been studying a resilient network whose key element is a movable and deployable ICT resource unit. The resilient network needs a function of robust and immediate connection to a wide area network that is active outside the damaged area. This paper proposes an application of digital coherent technology for establishing optical interconnection between the movable ICT resource unit and existing network nodes through a photonic network rapidly, easily, and with a minimum of manual work. We developed a prototype of a 100-Gbit/s digital coherent transponder that can be installed in our movable and deployable ICT resource unit and experimentally confirmed the robust and immediate connection by virtue of the plug and play function.

Recent Advances in Elastic Optical Networking

T. Tanaka and M. Jinno

IEICE Transactions on Communications, Vol. E97-B, No. 7, pp. 1252–1258, July 2014.

Many detailed studies ranging from networking to hardware as well as standardization activities over the last few years have advanced the performance of the elastic optical network. Thanks to these intensive studies, the elastic optical network is becoming feasible. This paper reviews the recent advances in the elastic optical network from the aspects of networking technology and hardware design. For the former, we focus on the efficient elastic network design technology related to routing and spectrum assignment (RSA) of elastic optical paths including network optimization or standardization activities, and for the latter, two key enabling technologies are discussed: elastic transponders/regenerators and gridless optical switches. Making closely dependent networking and hardware technologies work synergistically is the key factor in implementing truly effective elastic optical networks.

A Distributed Topic-based Pub/Sub Method for Exhaust-data Streams towards Scalable Event-driven Systems

R. Banno, S. Takeuchi, M. Takemoto, T. Kawano, T. Kambayashi, and M. Matsuo

Proc. of COMPSAC 2014 (the IEEE 38th Annual International Computers, Software & Applications Conference), pp. 311–320, Vasteras, Sweden, July 2014.

Distributed topic-based pub/sub has become indispensable for event-driven systems. There exist some methods achieving high scalability by using structured overlay networks. However, those methods involve inefficiency for “exhaust data” which has low or no value most of the time. In those methods, low-value data are gratuitously forwarded along multicast trees, and each publisher continues to forward such data to a relay node even if the data have no value. Consequently, network resources are wasted. To overcome these issues, we first defined a desirable property of overlay networks named “strong relay-free.” The strong relay-free property enables publishers and subscribers to compose connected subgraphs so that elasticity of the tree size and the ability to suspend publishing are realized. Subsequently, we propose a new method to construct topologies that satisfy the property using skip graphs. We implemented simulation programs of the method and confirmed that it achieved an improvement.

Low-loss Wavelength Routing Optical Switch Consisting of Small Matrix Switch and Cyclic Arrayed-waveguide Gratings for Colorless Add/Drop

T. Watanabe, S. Sohma, and S. Kamei

Japanese Journal of Applied Physics, Vol. 53, No. 8S2, 08MB02, August 2014.

We describe a new wavelength routing switch architecture that uses matrix switches and cyclic arrayed-waveguide gratings (AWGs). By devising connections between them, we construct a large port count optical switch using small port count matrix switches and AWGs. An 80 × 8 switch that consists of 8 × 8 matrix switches and 10 × 1 cyclic AWGs exhibits an insertion loss of only 4–7 dB. This switch enables us to make add/drop ports colorless in the existing reconfigurable optical add/drop multiplexer nodes.

Network Controlled Frequency Channel and Bandwidth Allocation Scheme for IEEE 802.11a/n/ac Wireless LANs: RATOP

B.A.H.S. Abeysekera, M. Matsui, Y. Asai, and M. Mizoguchi

Proc. of PIMRC (Annual IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications) 2014, Washington D.C., USA, September 2014.

The increased density of wireless LAN access points (APs) has induced inter-cell interference that severely degrades system performance. This problem seems to be getting worse with the increase in 802.11n- and 802.11ac-based APs, which establish basic service sets (BSSs) with wider channel bandwidths. In order to mitigate this problem, we propose an efficient radio resource allocation scheme called RATOP that can be applied to a managed wireless LAN system with a central coordinator. On the basis of channel monitoring results, capability, and data traffic information obtained from APs, the central coordinator computes the quasi-optimal frequency channel and channel bandwidth of each AP in such a way that the given utility function is maximized. Numerous simulations with UDP traffic flows on the coexistence scenarios of 802.11a/n/ac show that the RATOP works well and reduces the number of overlapping BSSs.
