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FEATURE White Paper on Quantum Network

Interview Building an International Hub for Quantum Security

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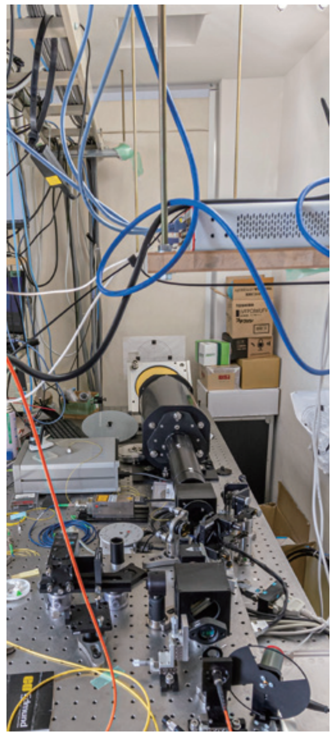


Cover Photo:
This is the White Paper on Quantum Networks released by NICT in March 2021. It compiles discussions among NICT staff working in diverse fields of research and occupations. While depicting the future society around 2035 in the form of a story, the paper identifies technical issues that require research and development by back-casting. The photo at the top right is the NICT Terminal, an optical space test bed (total length of approx. 8 km) connecting NICT and the University of Electro-Communications. The photo at the bottom right is the receiver of the quantum cryptographic equipment.

Photo Upper Left:
This photo shows the optical circuit inside the NICT Terminal of the optical space test bed (photo at top right on the cover).ly improve their range, flexibility, and mobility, etc.

Happy New Year

President of the National Institute of Information and Communications Technology
Dr. TOKUDA Hideyuki

We pray for the people who have passed away due to Covid-19. We deeply respect the medical staff who are working hard to care for and cure infected people as well as patients in serious conditions.
We also extend our sympathy to those affected by the storm, flood, and sediment disasters caused by Typhoons 9 and 14, and pray for an early recovery.

Last year saw a continuation of the COVID-19 pandemic from 2020, and efforts to prevent further spread of infection resulted in huge changes in the work styles of people, with dramatic shifts from analog and face-to-face interaction to digital and remote. Many people started using and became more familiar than ever with information and communications technology (ICT) such as video conferencing systems used for work-at-home, vaccination reservation systems, COVID-19 contact tracing apps, and simulations for predicting the number of infected people. At the same time, issues in existing work rules and workflows, as well as problems such as poor usability and compatibility of deployed systems, became more widely recognized.

As Japan's only national research and development agency specializing in the field of ICT, the National Institute of Information and Communications Technology (NICT) promotes ICT R&D from an integrated perspective, from the basic to the applied, while collaborating with universities, industry, local governments, and domestic and overseas research institutions and aiming to generate innovation by giving back to society with the results of our R&D. Furthermore, by flexibly responding to social issues on a global scale and using systems that integrate cyberspace and physical space, we aim to help realize a human-centered, sustainable, and inclusive society; in other words, a safe and secure Society 5.0.

Under the 5th medium- to long-term plan, which launched in April 2021, in addition to our main mission of promoting R&D and open innovation in five priority areas (Advanced electromagnetic technology, Innovative networks, Cybersecurity, Universal communication, and Frontier science) based on a new ICT technology strategy, we will actively promote R&D in the four strategic research fields of Beyond 5G (B5G), AI, Quantum ICT, and Cybersecurity.

In B5G R&D, with a game-changing mindset, we aim to become an R&D Hub in Japan based on collaboration with R&D projects that were commissioned by the Beyond 5G R&D Promotion Project. In the field of AI, we will further enhance multilingual voice translation technologies to provide simultaneous interpretation level functions by around 2025, aiming for a world without language barriers. In the field of Quantum ICT, we are promoting the activities of the Quantum ICT Collaboration Center, aiming to become an international research center for quantum security technology in the new building of the headquarters. In the field of cybersecurity, we will promote the activities of the Cybersecurity Nexus to build integrated cybersecurity knowledge and human resource training infrastructure, aiming to be a "nexus" between industry, academia, and government. In August of last year, we published two white papers in the two fields, B5G and quantum ICT, respectively. We will continuously update the contents of these white papers in the future to strengthen both our own R&D and our information communication capabilities, thus deepening our collaboration with research institutes and companies in Japan and overseas.

In addition, NICT will accelerate the spread of its R&D results throughout society by promoting activities to utilize the advanced technologies developed by NICT for businesses and other organizations, and creating a testbed environment for the open use of research-result data. We will also enhance activities such as NICT Quantum Camp (NQC) and SecHack365 for training the next generation of ICT human resources.

In terms of our management policies, in addition to the previous "COC" consisting of Collaboration, an Open mind and open innovation, and a Challenging spirit, we have added two new key concepts: the digital transformation (DX) of NICT itself; in other words, the DX not only of business processes but also R&D processes, and Computing & Communication for Carbon Neutral. We will further develop these policies under the banner of "COC 2.0."

NICT will continue to strive to further develop the ICT field by promoting collaborative activities between industry, academia, and government, while also cooperating and working with other stakeholders and welcoming opinions from a wide variety of people in Japan and overseas. We appreciate your support and cooperation.

Interview

Building an International Hub for Quantum Security

Beyond the current computers that work on bits, which are 0 or 1, quantum computers handle information as quantum bits that have a superposition state, 0 and 1. Quantum cryptography eliminate the threat to current cryptography posed by quantum computers. This new communication technology made possible by quantum dynamics is at the cutting edge.

The Quantum ICT Collaboration Center was established in April 2021 to lead the construction of a platform for quantum technology. We interviewed two people, SASAKI Masahide, Director General, and FUJIWARA Mikio, Director of the Quantum ICT Design Initiative, Quantum ICT Collaboration Center, and Quantum ICT Laboratory.

SASAKI Masahide

Director General, Quantum ICT Collaboration Center

Masahide Sasaki received Ph.D. degree in physics from Tohoku University in 1992. During 1992-1996, he worked in NKK (currently JFE Holdings). In 1996, he joined the Communications Research Laboratory (currently NICT). After serving as Director of Quantum ICT Laboratory and Distinguished Researcher of Advanced ICT Institute, he is presently Director General of Quantum ICT Collaboration Center. NICT Fellow since 2016.

FUJIWARA Mikio

Director of Quantum ICT Laboratory, Koganei Frontier Research Center, Advanced ICT Research Institute/
Director of Quantum ICT Design Initiative, Quantum ICT Collaboration Center

He joined the Communications Research Laboratory, Ministry of Posts and Telecommunications (currently NICT) in 1992. He has been engaged in research on satellite-mounted far-infrared detectors, photon number classifiers, cryogenic electronics, and quantum key distribution. Ph.D. (Science).

Leading NICT activities as the hub for quantum security

—— Director General SASAKI, what was the reason for establishing the Quantum ICT Collaboration Center?

SASAKI The direct impetus was the Quantum Technology Innovation Strategy established in January 2020 by the Integrated Innovation Strategy Promotion Council of the Japanese Government. The strategy is to bring together outstanding researchers and engineers as well as other resources inside and outside Japan, establish a system for organic collaboration between industry and academia, and comprehensively conduct everything from basic research to social implementation and human resource development by establishing a hub for quantum technology innovation.

There are eight hubs for respective target fields. NICT was assigned to the "quantum security hub," to play the central role in innovating and developing quantum security. The Quantum ICT Collaboration Center was established to enable NICT to do this properly.

—— Could you explain the specific activities of the Quantum ICT Collaboration Center and the outline of the organization?

SASAKI The activities of the Quantum ICT Collaboration Center can be roughly divided into four pillars (Figure 1).

The first pillar is "research and development," which is further divided into four themes: quantum basic technology, quantum security, satellite quantum communication, and quantum networks.

The next pillar is "implementation/testing," which carefully evaluates the reliability, etc. of the results of the research and development. An open test bed has been developed to enable more people to use the conventional quantum network test bed.

For the third, "social development," they are currently working on standardization. They are also defining the tasks of evaluation, verification, and certification.

The last pillar is "human resource development." Taking the long view, human resources are the basis of research and development. Last year, before the collaboration center was set up, a program for training young staff called "NICT Quantum Camp (NQC)" was started.

Organizationally, the Quantum ICT Collaboration Center consists of the Director General and his support staff, under which is the General Planning Office which organizes various collaborations. The research and development is conducted by the Quantum ICT Design Initiative. Director FUJIWARA is also the director of the Quantum ICT Laboratory. Of the four themes described above, research groups for three have been organized, and the team for developing the open test bed has been launched.

—— Director FUJIWARA, you are the Director of the Quantum ICT Design Initiative and the conventional Quantum ICT Laboratory. What is the role of the Quantum ICT Design Initiative and its differences from the Quantum ICT Laboratory?

FUJIWARA At NICT, the Quantum ICT Laboratory has been researching quantum technology for many years, and this is now its 21st year. Under the Advanced ICT Research Institute, the research institute will continue to focus on basic research with an eye to the future. On the other hand, the Quantum ICT Collaboration Center will be more involved in social activities such as creating new applications and services with private companies.

However, it is unproductive to draw firm lines between a series of procedures. While maintaining strong collaboration among the organizations, the mission of the Quantum ICT Laboratory and the Quantum ICT Design Initiative is to create a comprehensive flow.

White Paper and future prospects

—— The White Paper released this spring will surely be a significant part of the activities of the Quantum ICT Collaboration Center. What is the significance of the White Paper?

SASAKI Although some fields of quantum technology have been implemented, the target is research and development looking 20 to 30 years ahead. The White Paper summarizes what we can currently expect including a roadmap for research and development and an estimated future image of social contribution in the long term. Of course, we cannot develop quantum technology by ourselves; we need joint efforts by many people. Therefore, the White Paper is intended to inform others about our activities and encourage them to join us.

The background was the implementation of a plan for creating a strategic White Paper for the fields of quantum technology and Beyond 5G at the Innovation Design Initiative (IDI), a think-tank under the President, and the requests of staff. Almost 20 members were involved, including key figures and related departments concerning quantum technology. As researchers have different visions of the future, there have been some disputes. However, the task often made each researcher recognize an entirely different future. So it was a hard but rewarding process.

FUJIWARA When imagining the future, it is necessary to clarify what can be done with quantum technology and what cannot. It is not enough to talk about dreams; the researchers have to create a solid road map of how to implement them (Figure 2) and explain it. The White Paper serves as a blueprint.

It is only a forecast and so may not happen for sure. However, at least we hope our efforts will give many people a chance to think of how to merge cutting-edge technology and what systems should be established in order to create a better society.

—— Looking at the future, could you give a general message to researchers?

SASAKI It has been more than 20 years since the inception of quantum technology. Based on a platform developed by a Japanese team of industry-academia collaboration, we are approaching the next phase of conversion. This process is hard, but it is a key moment for researchers. We hope many researchers will join us.

—— Thank you very much.

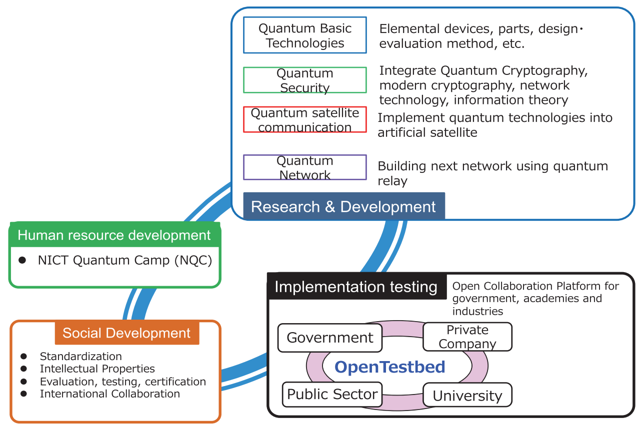


Figure 1 Promotion Strategy of Quantum ICT Collaboration Center

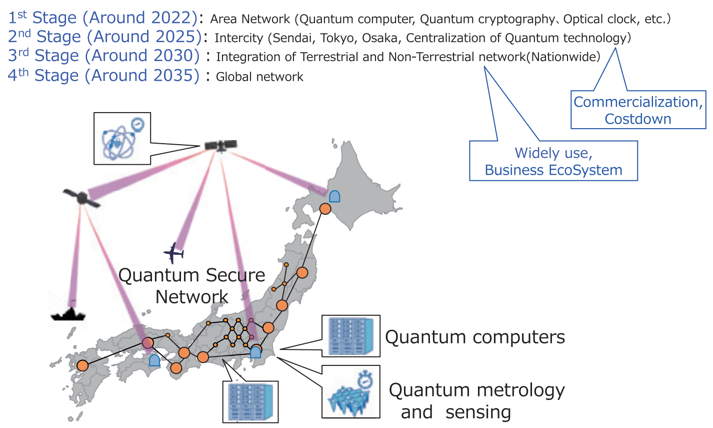


Figure 2 Roadmap of Quantum Technology Platform

Purpose and Expectation of the White Paper on Quantum Networks

IDE Shinji

Director of the New Generation Mobile Communications Office, Radio Department, Telecommunications Bureau, Ministry of Internal Affairs and Communications

Former Managing director, General Affairs Department/Strategic Planning Department, Secretary to the President, NICT.

Major countries have been working on the development of quantum cryptography, and beyond that, quantum networks. While the race to develop gate-based quantum computers is accelerating, there is concern that the cryptography used in current communication networks could be decrypted. It follows that it is necessary to conduct research and development and introduce quantum networks to secure the safety and reliability of communication. Against this background, NICT released a White Paper on quantum networks in March 2021.

Purpose and significance of the White Paper

Assuming the quantum internet as the ultimate goal, the White Paper summarizes the social image, elemental technologies, and implementation strategy realized by quantum networks. To implement a global quantum network, it is indispensable to appeal to researchers inside and outside Japan, and to collaborate with various stakeholders worldwide.

Overseas trends

The U.S., Europe, and China have drawn up research and development strategies on quantum technology including quantum networks as strategic basic technology, and have been investing heavily in research and development and human resources.

Based on the National Quantum Initiative Act, the U.S. has spent 1.2 billion dollars over five years in research and development of quantum information science from long-term perspective. They are also conducting research and development, demonstrating elemental technologies, and developing human resources towards the realization of the quantum internet.

In Europe, Quantum Technologies Flagship of the European Commission has been investing one billion Euro over five years on quantum technology research. In March 2020, they released the "Strategic Research Agenda on Quantum Technologies" with the ultimate goal of creating the quantum internet. In addition, 25 countries in Europe have agreed to build EuroQCI, a quantum test bed network for building the future quantum internet, while the OpenOKD project has been developing and demonstrating quantum cryptography technology and its applications.

Meanwhile, China launched the satellite "Mozi" in 2016, which succeeded in demonstrating quantum cryptography, etc. between the satellite and ground. They have built a guantum crytpgraphy communication backbone line between Beijing and Shanghai, as well as metropolitan networks in major cities. The total length of their quantum cryptography networks exceeded 7,000 km as of 2018. Moreover, many companies have been established to provide communication equipment, devices, and platforms, and now lead the world in the field of quantum cryptography.

Future prospects

In Japan, the "Quantum Technology Innovation Strategy" was released in January 2020. Under the strategy, NICT, as the Quantum Security Hub, has been conducting research and development of quantum network technologies, and nurturing human resources. The research and development projects of the Cabinet Office and the Ministry of Internal Affairs and Communications have also been working on establishing global quantum cryptography networks. Further technical development and efforts to define rules including international standardization are required. NICT is expected to lead these efforts and accelerate the implementation of global quantum networks in collaboration between industry and academia.

Figure 1 Cover page of Quantum Network White Paper

Quantum Cryptography Over Free-space Optical Links

Technology extending the possibilities of safe and secure networks

Figure 2 Portable optical ground station that stably receives the quantum signal from a satellite and can be deployed to various places

ENDO Hiroyuki

Research Manager, Quantum ICT Collaboration Center

He joined NICT in 2017. His research interests are in physical-layer cryptography and quantum cryptography over free-space optical links. Ph. D. (Science).

SAITO Yoshihiko

Senior Researcher, Space Communication Systems Laboratory, Network Research Institute

After working in National Astronomical Observatory of Hawaii and Tokyo Institute of Technology, he joined NICT in 2017. He is working on the research and development of free-space optical communication systems and adaptive optics systems. Ph. D. (Science).

TOYOSHIMA Morio

Director General, Wireless Networks Research Center, Network Research Institute

He joined CRL (currently NICT), in 1994. After engaging in ETS-VI laser communication experiments, he developed onboard satellite communication systems for OICETS, SOTA and ETS-IX. Ph. D. (Engineering).

For more than a decade, NICT has been focusing on quantum cryptography over free-space optical links, and conducting research and development of the technology. In the Quantum Network White Paper, the authors, who are involved in research and development of this technology, discuss ideas and depict the future networks that may result from this technology, such as basic networks for safely exchanging confidential information and security infrastructure which is securely open to everybody. This article describes quantum cryptography over free-space optical links.

Free-space optical (FSO) communication is a type of wireless communication using a laser beam, such as optical communication between a satellite and a ground. It is known that quantum cryptography in free-space optical communication resolves the conventional issues of quantum cryptography, thus greatly increasing the possibility of safe and secure networks.

Quantum cryptography between the satellite and the ground extends the reachable distance of quantum cryptography. In quantum cryptography through an optical fiber, the quantum signals attenuate exponentially with transmission distance mainly due to the absorption of photons by the optical fiber. In space, where there is no atmosphere, the main cause of attenuation is divergence of the beam diameter caused by diffraction of the laser beam. The rate of attenuation is proportional to the square of the transmission distance, which is lower than that of optical fibers. This is why photons can be sent over longer distances. Using a satellite as a relay, quantum cryptography even between continents is possible (Figure 1).

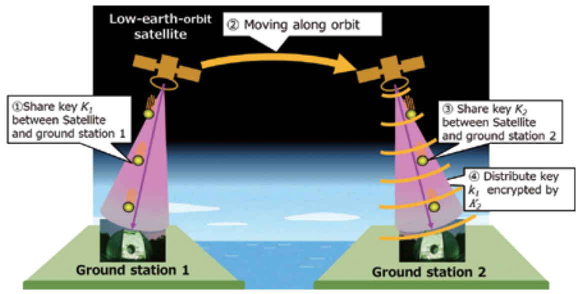


Figure 1 Schematic diagram of inter-continental cryptography using a satellite as a relay

In addition, using the features of FSO communication, it is possible to perform secure transmission faster than conventional quantum cryptography. Conventional quantum cryptography has been shown to be safe against eavesdroppers who have unlimited physical ability, attacking from various places. However, FSO communication uses a highly directional laser beam in a line-of-sight path between the sender and the receiver. Therefore, it is assumed that the only attack model that can be used by an eavesdropper is passive eavesdropping. Under such restriction on the eavesdropper, the technology for enabling secure transmission faster than conventional quantum cryptography is called physical-layer cryptography. This technology can be expanded to applications such as group key agreement among several parties, which is difficult with only conventional cryptography.

Since fiscal 2019, NICT has been participating in the national project, "Research and Development of Quantum Cryptography Technology in Satellite Communication (until FY 2022)," and developing a transceiver that can be used for quantum cryptography between a satellite and a ground. Several pieces of equipment are approaching completion (Figure 2). Demonstrations have been performed at NICT's premises and at Tokyo Skytree. Since FY 2021, based on the knowledge gained from the research, we have been participating in the new national project "Research and Development of Satellite Quantum Cryptographic Technology for Establishing a Global Quantum Cryptographic Communication Network (until FY 2025)," which is conducting research and development for realizing a global quantum cryptography network between low-orbit, middle-orbit, and geostationary satellites and the ground. Leveraging the results of these projects and future studies, we are continuing research in order to deliver the future depicted in the Quantum Network White Paper.

Quantum Cryptography and Quantum Key Distribution Network

Toward social deployment of computationally unbreakable cryptosystems

TAKEOKA Masahiro

Research Executive Director, Advanced ICT Research Institute

He joined CRL (currently NICT), Japan, in 2001. His research interests include quantum optics, quantum information theory, and quantum cryptography. Since April 2021, he has been a professor of at Keio University, and also a research executive director at Advanced ICT Research Institute of NICT.

The conventional cryptography that underpins today's information society is facing the risk of decryption as quantum computers become more powerful. Meanwhile, quantum cryptography is currently the only cryptographic system that has been mathematically proved to be impossible to decrypt with any computer, including future large-scale quantum computers. We take a look at the efforts and future prospects for research and development, and the implementation of a quantum key distribution network, which is the core technology of quantum cryptography.

Cryptographic technology which underpins today's networked society, and its issues

The security of the cryptography that is widely used today is guaranteed by "computational security," which means that extremely massive computing power is needed for decryption. This allows us to safely exchange data every day. However, today's cryptography is facing the potential threat of becoming easily decrypted due to the advent of large-scale quantum computers and entirely new computational technology/mathematical algorithms in future. Especially, critical information that requires secrecy for decades is at risk of "harvest now, decrypt later" attacks, in which encrypted data is eavesdropped or acquired, and then decrypted in future when new computational technology is developed. This is why an urgent response is required.

Two new types of technology are being developed to address this issue. One is "post-quantum public-key cryptography," which has the same computational security but has a mathematical structure that is thought to be difficult to decrypt with currently known quantum calculation algorithms, and it is now being implemented and standardized. The other type is quantum cryptography, as explained below. Quantum cryptography is currently the only cryptographic system that has been proved to be safe and impossible in theory to decrypt with any computational technology or computers in future ("information-theoretic security").

Quantum cryptography and quantum key distribution (QKD) network

As shown in Figure 1, quantum cryptography consists of two steps: quantum key distribution (QKD) and one time pad (OTP) encryption. QKD is a technology for the sender and receiver to share a secret key that is kept secure against third parties, which uses quantum mechanical properties of light signals, such as photons. OTP encryption encrypts data using an encryption key having the same size as the data and, once a key is used, it will not be reused. Using the encryption key provided by QKD achieves information-theoretic security. OTP encryption and the sending and receiving of encrypted data are all performed with normal computers and communication lines; only the QKD part requires quantum technology.

The technology for managing and distributing keys safely and efficiently by connecting QKD transceivers to the network is called a quantum key distribution (QKD) network (Figure 2). By sharing the encryption key at any point on the network with the QKD network, and providing the key to the conventional network, it is possible to provide new security services using an information-theoretic secure cryptographic key. In addition to QKD networks connected with optical fibers, QKD using satellite communication is also under development, which is expected to be integrated into a global QKD network in future.

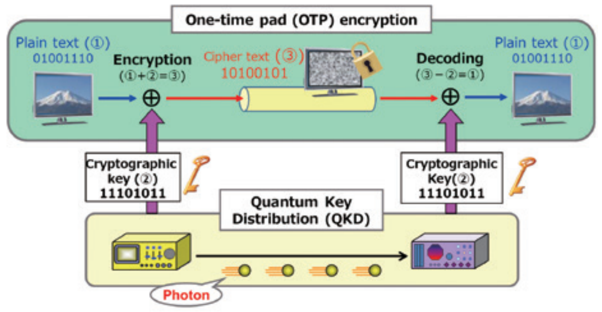


Figure 1 Mechanism of Quantum Cryptography

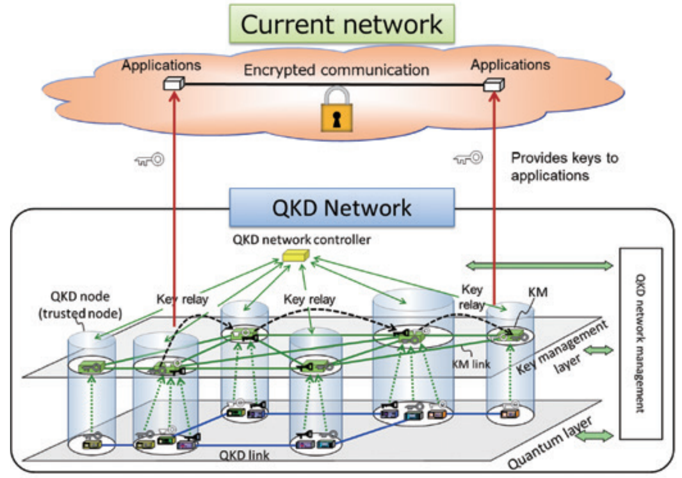


Figure 2 Key delivery from Quantum Key Distribution (QKD) Network

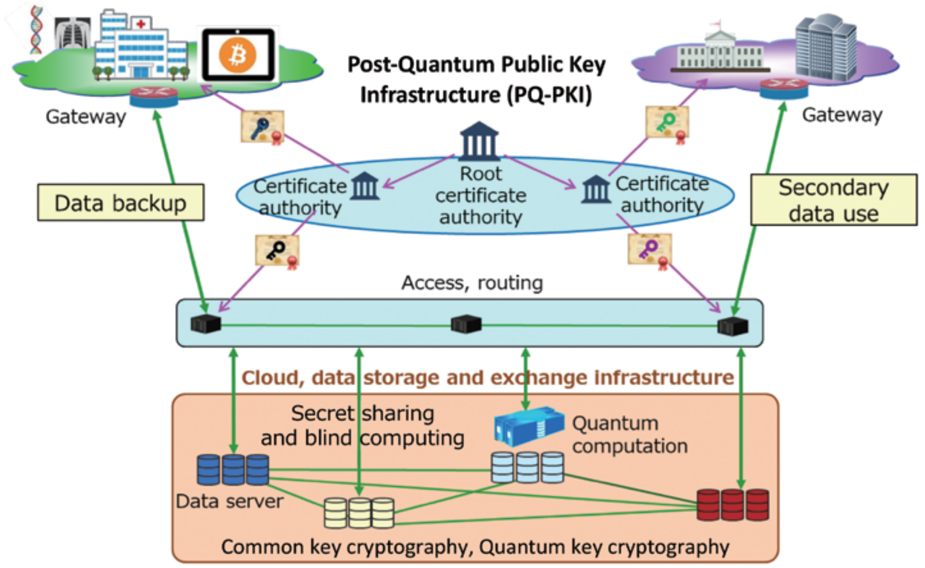


Figure 3 Quantum Secure Cloud Technology

Research and development, and efforts toward implementation

Since the 2000s, in collaboration with universities and companies, NICT has been developing the technology for QKD systems and their networking technologies, such as QKD network control and management technologies, and has also conducted field demonstrations. In 2010, Tokyo QKD Network, a test bed constructed in collaboration among industry, academia, and government, recorded the longest operation time in the world, and various demonstrations of principle and practice are being conducted. Regarding implementation, companies in Japan, Europe, and China have commercialized QKD devices. Moreover, telecom carriers and start-up companies around the world have been working toward the commercial provision of services using the QKD network.

For the QKD network technology to spread globally, international standardization is crucial. In collaboration with the government, companies, and universities, NICT is actively working toward international standardization at the International Telecommunication Union Telecommunication Standardization Sector (ITU-T), International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC SC1), European Telecommunications Standards Institute (ETSI), etc. Especially, at ITU-T, Japan is leading the development and publication of many recommendations, including for international standardization of QKD networks.

Exploitation of QKD networks and future prospects: Quantum secure cloud technology

To apply the high secrecy of quantum cryptography in society, it is necessary to develop application technologies by taking a broad view of communication systems and security technology as a whole. One of those technologies is quantum secure cloud technology, which is being developed by NICT in collaboration with industry and academia. This enables the storage and computational processing of data backups that cannot be decrypted or tampered with by any computers, by merging authentication infrastructure and blind computing with quantum cryptography, secret sharing, and post-quantum public-key cryptography (Figure 3). By storing data in several servers in a distributed, encrypted form, this technology realizes both information-theoretic security, in which even if the information in some servers is leaked, the original data cannot be restored, and availability, in which if the information in some servers is lost, the original data can be restored from the remaining information at the same time. This proprietary technology was developed in Japan, and NICT and companies are conducting demonstrations of storing important data in various fields including the medical industry. It is expected that a new security infrastructure for the networked society will be developed by properly merging the QKD network with various contemporary security technologies. The NICT Quantum Network White Paper describes the principle of the technology, requirements, and prospects for social implementation in detail.

Quantum Interface Technology

Generating quantum entanglement between remote matter systems via telecom photons

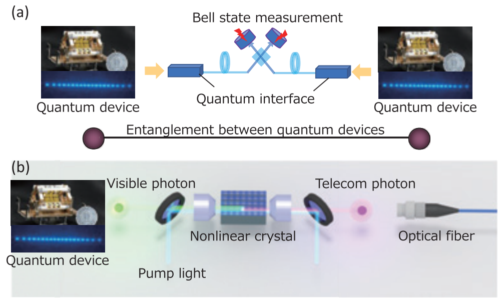
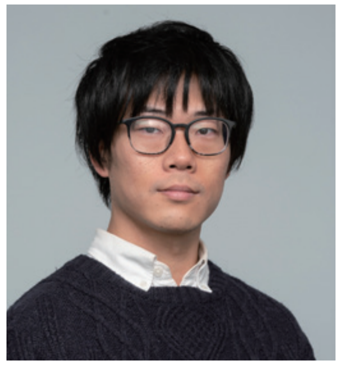


Figure 1 a) Quantum devices at distant nodes are entangled by performing Bell measurement on the photons entangled with the quantum devices.
b) Schematic of quantum wavelength conversion



TSUJIMOTO Yoshiaki

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After getting his Ph.D. in Physics, he joined NICT in 2017. He is engaged in developing entangled photon pair sources and experimental demonstration of the quantum protocols. Ph. D. (Science).

HAYASAKA Kazuhiro

Associate Director, Quantum ICT Laboratory, Advanced ICT Research Institute

He joined the Communications Research Laboratory (currently NICT) in 1990 after finishing his graduate studies. His research activities cover quantum optics with trapped ions. He is a specially appointed associate professor at Graduate School of Engineering Science of Osaka University. Ph.D. (Science).

YOSHIHARA Fumiki

Senior Researcher, Quantum ICT Laboratory, Advanced ICT Research Institute

After getting his Ph.D. in Engineering and working at RIKEN, he joined NICT in 2014. He is engaged in research on quantum information processing based on superconducting quantum circuits. Ph.D. (Engineering).

The ultimate network that can achieve maximum functionality allowed by physical principles by entangling quantum devices is called a quantum network. To generate quantum entanglement between remote matter quantum systems, it is necessary to prepare telecom photons that are entangled with each quantum system, and to observe quantum interference between them. Here, we outline the quantum interface that generates telecom photons entangled with the matter quantum systems.

Quantum devices such as quantum computers, quantum memory, and quantum sensors consist of various matter quantum systems such as superconducting materials, single atoms, and ion-traps, and it is impossible to directly generate quantum entanglement among these devices. Therefore, photons entangled with the quantum devices are necessary to mediate the entanglement generation. For example, in the case of an ion-trap, entanglement between the energy level of the ion and the polarization of the photons can be generated. By performing an interference measurement called Bell state measurement on the photons, it is possible to generate quantum entanglement between quantum devices (Figure 1(a)).

The photons generated by a matter quantum system have a wavelength specific to each matter ranging from visible to near-infrared for atoms and ions, and in the microwave band for superconducting materials. However, these wavelengths significantly attenuate in transmission channels such as optical fiber and strip lines, making it impossible to transmit photons to distant locations. Therefore, an interface is required, which converts only the wavelength of the photon to a wavelength that is suitable for long-distance communication while maintaining the quantum state. Such conversion technology is generally called a quantum interface, and has attracted intense research and development in recent years both in and outside Japan.

The main method for conversion from visible to telecom wavelengths uses the second-order nonlinear optical effect, which was demonstrated by a group at Osaka University in 2011. This method can convert visible photons to telecom photons with an efficiency of 100% in principle by feeding the photons to be converted and strong pump-light simultaneously into a nonlinear optical crystal (Figure 1(b)). In a joint effort with Osaka University and the University of Sussex, NICT has succeeded in wavelength conversion from fluorescent photons from Ca+ ions (wavelength: 866 nm) to a telecom wavelength of 1,530 nm, and transmitting them through a 10-km optical fiber.

In the case of superconducting qubits, since the wavelength of the photons that can interact is in the microwave band, a quantum interface that converts microwave wavelengths to telecom wavelengths is required. NICT has been conducting research and development of a quantum interface that coherently converts microwave photons to telecom photons using surface acoustic waves.

In the future, it is expected that quantum interfaces will be made more efficient and miniaturized by integrating the device into a chip.

Quantum Sensing

Quantum Network of Optical Clocks

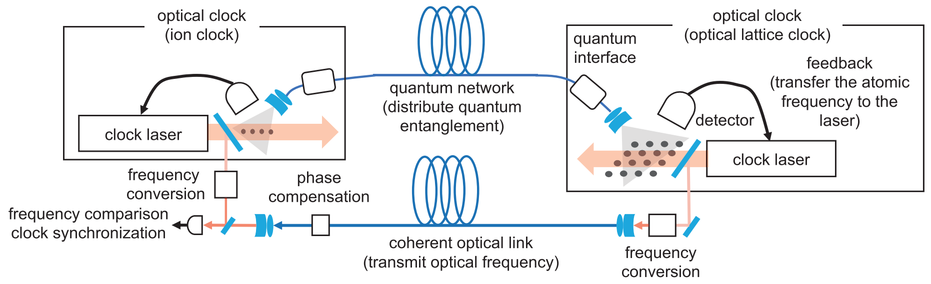
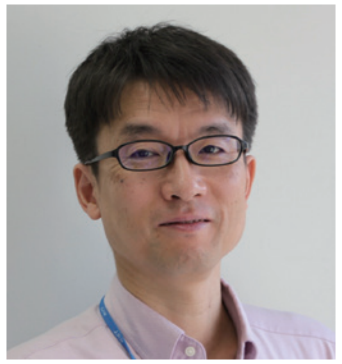


Figure 1 Basic configuration of the quantum network of optical clocks

HAYASAKA Kazuhiro

Associate Director, Quantum ICT Laboratory, Advanced ICT Research Institute

He joined the Communications Research Laboratory (currently NICT) in 1990 after finishing his graduate studies. His research activities cover quantum optics with trapped ions. He is a specially appointed associate professor at Graduate School of Engineering Science of Osaka University. Ph.D. (Science).



IDO Tetsuya

Director of Space-Time Standards Laboratory, Radio Research Institute

He joined NICT in 2006 after post-doctoral research in ERATO Project and JILA. His research activities cover time and frequency metrology. Ph.D. (Engineering).

Measuring physical quantities using quantum effects is called quantum sensing, and various applications are expected to be made possible by networking quantum sensors. An atomic clock is a quantum sensor that measures space-time, and its optical frequency version is called an optical clock. Here we give an overview of a quantum network of optical clocks.

It is known that the time taken to measure physical quantities can be reduced by exploiting a quantum effect called quantum entanglement. In general, measuring a physical quantity with N particles is expected to reduce the time by $1/\sqrt{N}$ compared to measurement with a single particle. Using entanglement, it is possible to reduce this time to $1/N$. In the case of $N = 100$, there is a ten-fold difference between the measurements with and without entanglement. An optical clock measures the frequencies specific to neutral atoms and atomic ions, and variations in space-time via variations in the frequencies. By connecting optical clocks that consist of N atoms located at M sites, the measurement time can be reduced to $1/\sqrt{NM}$ without entanglement, and the reduction factor can be boosted to $1/NM$ if entanglement can be distributed to all the atoms. In addition, the time taken to measure space-time variations at a site via the frequency variation measurement can be reduced in the same way by using entanglement. A network of atomic clocks that accelerate space-time synchronization and the observation of space-time variations using entanglement has been proposed, and it is called a "quantum network of optical clocks."

A quantum network of optical clocks requires a coherent optical link that faithfully transmits the frequency accuracy of an optical clock. In Europe, a coherent link of optical clocks with a total length of more than 2,000 km is under construction. In Japan, research and development of a coherent optical link among the Institute of Physical and Chemical Research (RIKEN), the University of Tokyo (U. Tokyo), NTT, and NICT is underway, and a link with a total length of 240 km has been reported. In an experiment with a 60-km optical fiber conducted by NICT and U. Tokyo in 2011, we succeeded in observing a frequency shift in real time caused by general relativity due to an altitude difference of 56 m between the NICT headquarters and the Hongo Campus of U. Tokyo

However, to reduce the space-time measurement time to the quantum limit it is necessary to distribute entanglement through a quantum network to the optical clocks connected with a coherent optical link (Figure 1). To do this, it is necessary to maintain entanglement between the atoms in the optical clocks and the photons that distribute optical entanglement. For ion optical clocks, NICT succeeded in generating single photons in quantum states correlated to calcium ions (Ca^{+}) in collaboration with the Max Planck Institute of Quantum Optics in 2004. The wavelength of 866 nm of the photons in the experiment is specific to Ca^{+}, and is not suitable for transmission through an optical fiber. However, in 2018, NICT demonstrated 10 km transmission in an optical fiber in a joint effort with Osaka University and the University of Sussex. In the experiment the photons were converted to a wavelength appropriate for the fiber transmission (1,530 nm), and the quantum state was preserved over the transmission.

The integration of these technologies demonstrated by NICT and other technologies including the generation of entanglement between atoms and its distribution with photons pave the way to the quantum network of optical clocks. To contribute to its realization, NICT is conducting research and development to enhance the accuracy of optical clocks using quantum effects, and to demonstrate a quantum network.

To Realize Quantum Networks

Construction, Control and Management of Terrestrial/Satellite Integrated Global Quantum Networks

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Network Architecture Laboratory,
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He joined NICT in 2007. His research interests include network control and management technologies. He has been in the current position since April 2021.

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He joined CRL (currently NICT), Japan, in 2001. His research interests include quantum optics, quantum information theory, and quantum cryptography. He has been a professor of Keio University, and also a research executive director of Advanced ICT Research Institute, NICT, since April 2021.

TOYOSHIMA Morio

Director General,
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Network Research Institute

He joined the Communications Research Laboratory, Ministry of Posts and Telecommunications (currently NICT), in 1994. After engaging in ETS-VI laser communication experiments, he was transferred to NASDA (currently JAXA), and after doing research at Vienna University of Technology, worked on the research and development of onboard satellite communication systems for OICETS, SOTA and ETS-IX. Ph. D (Engineering).

Future quantum applications are expected to be realized by around 2040, including the construction of a global quantum network (Quantum Internet), ultra-long-distance quantum cryptography and distributed quantum computing, space-time synchronization of a quantum network of optical clocks, and quantum sensor networks. This article introduces the technologies needed for the control and management of the global quantum network that integrates the terrestrial system with the satellite system.

■ Quantum network technology that supports long-distance, highly safe communication services and applications in the future

Thanks to the advancement of quantum key distribution (QKD) technology and related equipment, communication with quantum encryption is expected to be deployed in social infrastructures. The method for expanding distances and networking with trusted nodes that relay the secret key in electrical processing is expected to be realized at an early stage. However, since there is a limit to expanding the distance of point-to-point QKD because the relay points are not perfectly safe and the end points cannot directly share quantum information, it is difficult to realize future applications including large-scale distributed quantum computing and secret quantum computation, space-time synchronization with a quantum network of optical clocks, and quantum sensor networks. To resolve this, research and development is underway globally, as well as discussions on international standardization to create a global quantum network (Quantum Internet) that directly exchanges quantum information over long distances using quantum memory and quantum interface technology to interconnect quantum computers and quantum sensors, and integrates the terrestrial system with the satellite system. In the future, the construction of a large-scale quantum network to implement these applications is expected to enable sophisticated social and economic activities that contribute to enhancement of security, safety, and convenience for people. (See Figure 8, p.14 of “NICT Quantum Network White Paper*”.)

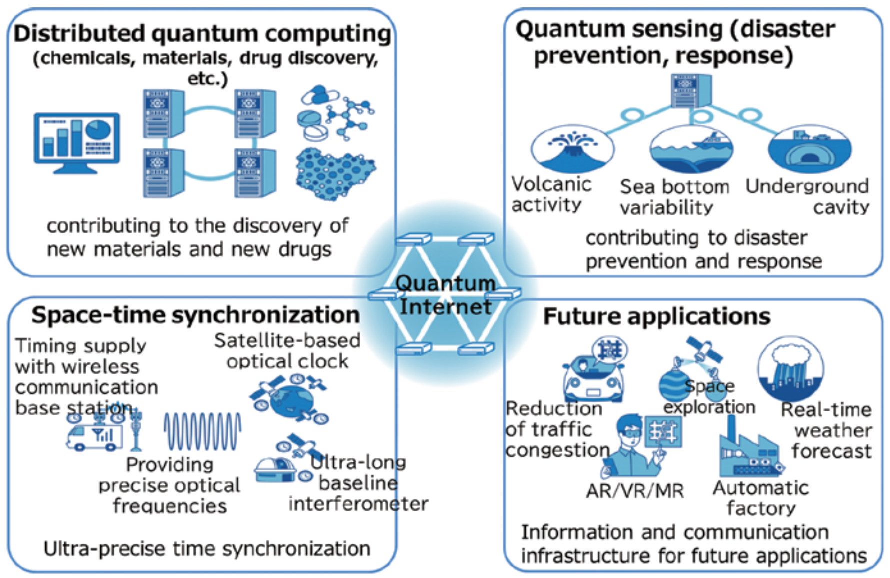

Figure 1 Examples of applications which are expected to be realized in quantum networks

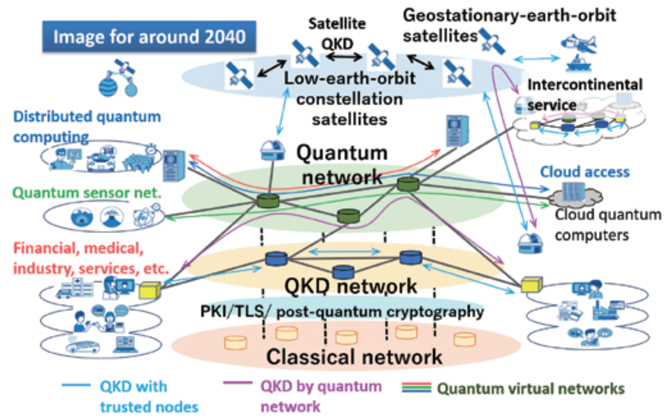

Figure 2 Schematic diagram of the progress of quantum networks around 2040

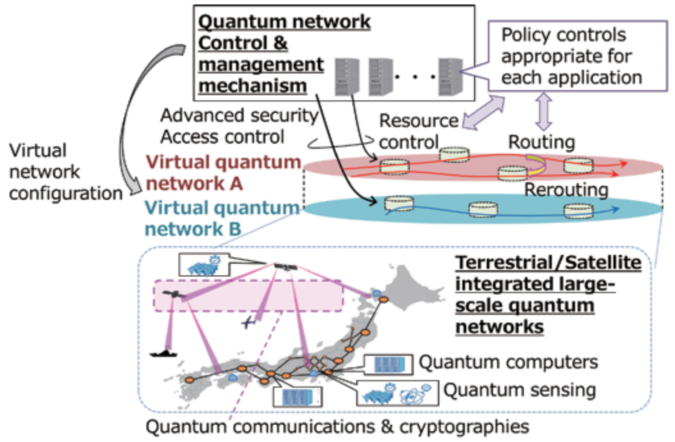

Figure 3 Image of control and management of terrestrial/satellite integrated large-scale quantum networks

■ Virtual quantum network technology that accommodates different types of quantum networks

As technology progresses, the service operation of a QKD network, the realization of quantum networks using quantum relays, mixing QKD and classical networks, and the expansion of QKD network services by interconnecting terrestrial and satellite systems are expected to spread and be developed in stages from the late 2020s to 2030s. By around the 2040s, it is expected that a global quantum network integrating the terrestrial system with the satellite system will be constructed, and virtual quantum network technology and services will be realized that accommodate various types of quantum networks and protocols for diverse quantum applications as well as QKD in a common physical network infrastructure (Figure 2). (See Figure 13, p.18 of “NICT Quantum Network White Paper*”.) By using virtual quantum network technology, it should be possible to satisfy the requirements and demands (size of the secret key, communication performance, stability of quantum applications, etc.) of various applications while saving costs by reducing the physical equipment managed by the network operator. In the future, infrastructure providers and virtual network operators (VNO) will likely construct various virtual quantum networks, and provide quantum applications stably and at low cost at the request of quantum application providers and content providers.

■ Control and management technology for quantum networks

To exploit the advantages of virtual quantum network technology, such as efficient use of resources and provision of various services, technologies for efficiently controlling and managing the entire quantum network are required (Figure 3). (See Figure 23, p.29 of “NICT Quantum Network White Paper*”.) To construct a virtual quantum network that satisfies the requirements and demands of various applications, and to respond to the changes in situations such as traffic fluctuations and fault detection in the network, it is important to implement dynamic and agile control mechanisms including routing and resource allocation to improve the stability of applications. In addition, it is effective to apply policy control (for example, software defined network (SDN) and in-network computing technology (for example, information-centric networking and network coding)) that has been studied actively in classical networks. Moreover, sophisticated security technology for guaranteeing the security and safety of the control and management mechanism and terrestrial-satellite integration technology for realizing a global virtual quantum network will be essential in future quantum networks.

■ Future prospects

As quantum technologies become more widespread and sophisticated, the realization and social deployment of various quantum applications including quantum cryptography will gain momentum. It is also necessary to construct global quantum networks, virtualize quantum networks to provide various application services in the future, and develop quantum network control and management technologies for realizing them. NICT will continue research and development of underlying technologies such as virtualization technology and routing technology, and security enhancement technology in order to implement quantum networks based on the future progress of quantum devices.

＊https://www2.nict.go.jp/idi/common/pdf/NICT_QN_WhitePaperJP_v1_0.pdf

New Technology Presentation Meetings by NICT

Intellectual Property Promotion Office, Innovation Promotion Department

On October 14, 2021, NICT and the Japan Science and Technology Agency (JST) held the "New Technology Presentation Meetings by NICT," which was conducted online due to the spread of Covid-19. In this presentation, the researchers directly described their patents to staff from private companies with the aim of implementing the results of research by public research institutes. A total of four technologies (Table) were presented by the researchers who invented them. They include a technology for improving the resolution at deep parts of a fluorescence microscope 3D image; a technology for manufacturing organic electro-optic polymer devices with low absorption loss of terahertz waves; physical layer cryptography that enables safe, high-speed, and long-distance communication; and a platform in which several people share the same experience in a virtual space. Different from academic presentations, they compared their invention with conventional and competing technologies; explained the features of the new technologies and possible applications; and solicited partnerships by explaining their expectations to the companies at the end.

There were 438 applicants from small to large companies, and many people attended. After the presentation, we received many questions and offered consultations in the technical consultation/question room provided, reflecting the high interest in NICT's technologies.

Even after the presentation, we received questions and requests for consultation, to which we replied individually. To deploy the results of research and development in practice by turning the contents of the presentation into collaborative research and technical transformation, NICT will promote collaboration with industry while considering technical needs.

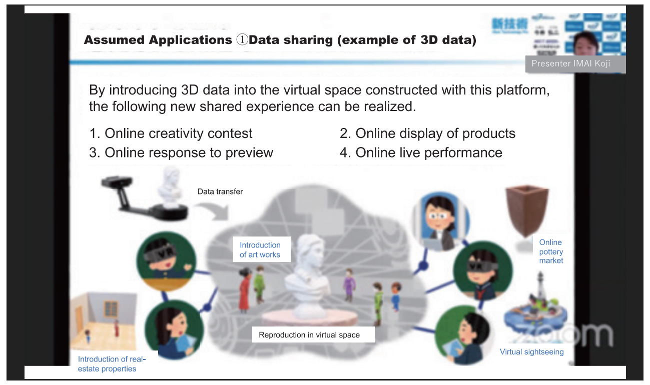

Figure Distribution of the presentation (IMAI Koji, Innovation Producer)

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(in Japanese)

TABLE Four new technologies presented at the meeting

	TITLE of Presentation	Abstract
1	Fluorescence microscope suitable for real-time observation of the deep regions of living biological samples	A fluorescence microscope, which is used for observing the deep regions of a living biological materials such as the brain, suffers a reduction in resolution due to optical aberration caused by the thickness of the biological sample. This technology improves the resolution of the deep regions only by arithmetic processing of 3D images without requiring a special device. It can improve the resolution at low cost, high speed, and with ease, without requiring excessive optical radiation, which is biotoxic.
2	Organic electro-optic polymer device technology toward Beyond-5G wireless communication	Organic electro-optic polymers enable ultra-high-speed optical modulation at several hundred GHz or more with high efficiency. They are expected to be used to convert from wireless signals to optical signals in radio over fiber (RoF) in the age of Beyond-5G, sensing of electric fields, and generation and detection of wide-band terahertz waves (0.1 to 10 THz). The new technology has enabled the development of devices with far lower terahertz loss.
3	Physical-layer cryptography toward safe and secure global networks	Using the properties of free-space optical communication such as high directivity and line-of-sight configuration, physical-layer cryptography can realize high-speed and long-distance cryptographic communication while maintaining the security against Eve with unbounded computational power. This technology enables physical-layer cryptography that can be installed in moving platforms (e.g., drones and aircraft) with ease, and can withstand disturbances induced by atmospheric fluctuations.
4	Shared experience platform in the new normal society	Several people can share an experience in various scenes in a virtual space. It is possible to share 360-degree actual images and 3D scan data, and to maintain the connection between users even after the scene is changed. Therefore, users are expected to gain new experiences with each other in an actual image space with enhanced presence.

Development of Quantum Optical Control Technology toward the Realization of Future Quantum Networks

TSUJIMOTO Yoshiaki

Researcher (Tenure-track),
Quantum ICT Laboratory,
Advanced ICT Research Institute
Ph.D. (Science)

Biography

1989: Born in Nara Prefecture.
2012: Graduated from the Department of Electronic and Materials Physics, School of Engineering Science, Osaka University.
2017: After graduating from the Department of Materials Engineering Science, Graduate School of Engineering Science, Osaka University, joined NICT.

Awards, etc.

2014: Tokui Award (Graduate School, Osaka University)

Q&As

Q What is good things to be a researcher?

A I like thinking of mysterious things. I enjoy it when my interests contribute to my job.

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

A Picking up plants in mountains and parks and cooking them. Various plants can be collected in each season. In autumn, I recommend yam bulblets and ginkgo nuts.

Q What advice would you like to pass on to students aspiring to be a researcher?

A Being optimistic is most important. When I feel lost, I think "something will turn up".

Quantum information science was born by the merging of information theory and quantum mechanics. Quantum mechanics deals with many counterintuitive physical phenomena such as uncertainty relations and quantum entanglement. Quantum information science is interesting because these counterintuitive phenomena enable various functions which cannot be realized by conventional information processing technology.

Today, the major target in the field of quantum information science is the construction of a quantum network that connects and networks quantum devices at distant locations by quantum entanglement. Quantum entanglement is a quantum correlation that cannot be explained with classical physics. Sharing quantum entanglement among distant communication nodes enables quantum protocols such as distributed/blind quantum computation and ultra-high-precision clock synchronization. Quantum information is encoded in various physical systems such as atoms, electrons, and light, but it is only photons, which are quanta of light, that can be used for quantum communication. In other words, to construct a quantum network, a technology for generating and controlling photons is indispensable.

I have been developing entangled photon pair sources based on the nonlinear optical effect, called "spontaneous parametric down-conversion." Such photon pair sources require sophistication without degrading the quality of the quantum entanglement. We have succeeded in developing a new ultra-high-speed entangled photon pair source by combining the high-speed electro-optical modulation technology used for photonics experiments and a highly efficient waveguide-type nonlinear optical crystal. The invention has raised the clock rate of generating entangled photon pairs to the order of GHz.

To realize a quantum network, it is necessary to develop various fundamental technologies such as quantum memory and quantum interfaces, as well as to develop more sophisticated quantum-optical technology. We will continue conducting research and development of these quantum technologies.

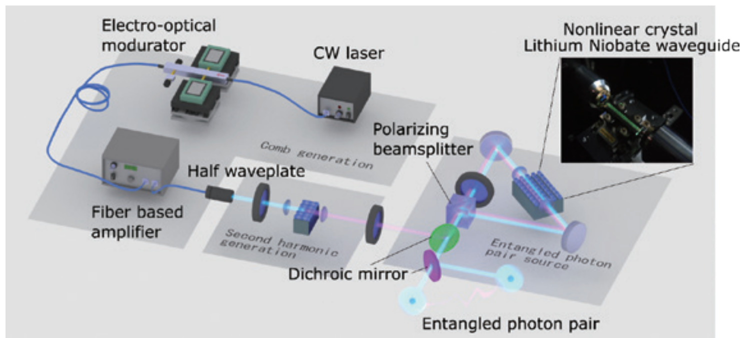

Figure Developed high-speed quantum entangled photon pair source

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