Press Release

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Nippon Telegraph and Telephone Corporation
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Field： Natural Science
Key words： quantum information, quantum repeaters, quantum internet, quantum cryptography, quantum computer

First proof-of-principle experiment of quantum repeaters with all photonics

— First big step towards a ‘quantum internet’ as the Holy Grail of information-processing networks —

【Points of achievement】

- A quantum internet enabled by quantum repeaters is the Holy Grail of information-processing networks
- A first proof-of-principle experiment of quantum repeaters has been done by adopting all-photonic quantum repeater protocol
- This is a first big step towards an energy-efficient high-speed global ‘all-optical’ quantum network

❖ Abstract

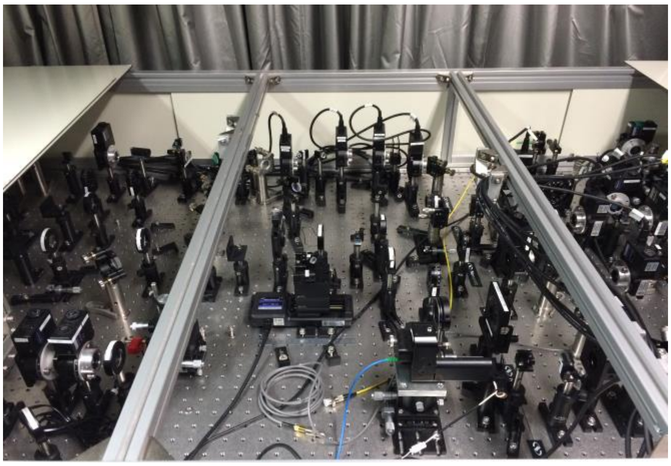

Figure 1: Experimental setup for all-photonic quantum repeaters

A research team of Prof. Takashi Yamamoto and Assistant Prof. Rikizo Ikuta at Osaka University and a research team of Dr. Koji Azuma at Nippon Telegraph and Telephone Corporation (NTT), collaborating with Emeritus Prof. Nobuyuki Imoto at Osaka University, Prof. Kiyoshi Tamaki at University of Toyama and Prof. Hoi-Kwong Lo at University of Toronto, have succeeded in demonstrating a first proof-of-principle experiment of quantum repeaters, by adopting all-photonic quantum repeater protocol[*1] which enables a global quantum network only with optical devices.

The current Internet is performed over a global optical-fibre network, where long-distance communication is enabled by repeaters. An all-optical-network approach, which is to perform communication with all such communication devices made with optical components only, holds promise for an energy-efficient high-speed Internet. The quantum version of this all-optical approach, called ‘all-optical quantum network’, is realizable by replacing the conventional repeaters with all-photonic quantum repeaters, which leads to a future ‘quantum internet’[*2] with applications far beyond the current Internet. The all-photonic quantum repeater protocol was proposed in 2015 as a promising protocol that is implementable only with optical devices, in contrast to conventional schemes necessitating matter quantum memories[*3]. However, since the all-photonic protocol is based on a new principle, called ‘time-reversal’ enabled only with quantum entanglement[*4], demonstrating this principle experimentally is regarded as a first big step towards the realization of not only all-photonic quantum repeaters but also the quantum internet.

Here Prof. Yamamoto's group in Osaka University, with collaboration with NTT, University of Toyama and University of Toronto, has successfully demonstrated a key component of all-photonic quantum repeaters, the time reversal, experimentally. This corresponds to a first proof-of-principle experiment of all-photonic quantum repeaters.

The present demonstration shows that not only all-photonic quantum repeaters but also a global all-photonic quantum internet is possible once ultra-low loss integrated optics and efficient entanglement light sources are available. At the same time, the current demonstration corresponds also to a first proof-of-principle experiment of an 'adaptive Bell measurement' [*5] which is required for arbitrary quantum repeater schemes (including conventional approach with matter quantum memories), implying that all-optical approach is one-step closer to the realization of quantum repeaters than conventional approaches.

This work will be published in the journal *Nature Communications* on 28th January, 2019.

❖ Background

In modern physics, quantum mechanics is the most accurate theory to describe phenomena in the nature, including behaviours of microscopic particles such as elementary particles and atoms. This quantum mechanics predicts a quantum computer as the ultimate computer allowed in the nature and quantum communication as the corresponding version of communication, the whole of which is now called quantum information processing. Given that the current internet connects information-processing devices in the world, a 'quantum internet' will play the role of connecting arbitrary 'quantum' information-processing devices all over the world, which is regarded as an ultimate information-processing network allowed by quantum mechanics. In fact, it is known that such a quantum internet would have many applications. For instance, the quantum internet would enable arbitrary users to perform information-theoretic secure communication using quantum key distribution, even if eavesdroppers in the network are allowed to use universal quantum computers freely. This highly secure communication can be used for a referendum, a top-level meeting, a financial deal, an exchange of genetic/biological information and so on. Further, the quantum internet enables any client to teleport unknown quantum states of their system to another at the speed of light, which is the basis of distributed quantum computing, quantum cloud computing and, ultimately, large-scale quantum computer networks. Besides this, the quantum internet could be used for synchronizing atomic clocks with unprecedented stability and accuracy, in a completely secure manner. It would also enable us to make baselines of telescope arrays unprecedentedly longer, contributing to the progress of astronomy. Therefore, a worldwide race towards building up the quantum internet with these fascinating applications has now started. China has launched even a satellite to achieve long-distance quantum communication, the EU has started a project for the quantum internet with a budget of about 30 million Euros, and the US has just announced the preparation of a large budget (about 1.2 billion US dollars) for quantum technologies, called the 'National Quantum Initiative Act', including researches towards a future quantum internet.

To realize such a quantum internet with an existing global optical-fibre network, current repeaters—which are used to perform conventional communication against photon loss of optical fibres—should be replaced with 'quantum' repeaters. Although the realisation of quantum repeaters had been believed to necessitate demanding matter quantum memories, this belief was disproved in 2015 by a proposal of 'all-photonic quantum repeaters', which works without any matter quantum memory, that is, only with optical devices. This all-photonic scheme has various advantages which are not held by conventional schemes with matter quantum memories. For instance, the communication rate is independent of communication distances, and thus, it realizes a high-speed quantum internet. The scheme does not need any interface between photons and matter. The proof-of-principle demonstrations of all its optical components have already been done. In principle, it works at room temperature. And, the scheme is easier to realize than an all-optical quantum computer[*6]. However, since the scheme is based on a new principle, called 'time-reversal', enabled only with quantum entanglement, demonstrating this principle experimentally is considered to be a first big step towards the realization of the all-photonic quantum repeaters.

❖ Research result

The research group in Osaka University, in collaboration with theoretical research groups in NTT, the University of Toyama and the University of Toronto, experimentally demonstrated, for the first time, a key component of the all-photonic quantum repeaters — the time-reversed adaptive Bell (TRA Bell) measurement, corresponding to a first proof-of-principle experiment of all-photonic quantum repeaters.

In general, the main task of quantum repeaters is to perform an adaptive Bell measurement that implements Bell measurement—which creates a quantum entanglement in a sense—only on survived photons at a repeater node. In typical repeater protocols, this task is performed with the help of matter quantum memories that can keep quantum states of the survived photons until the measurement. On the other hand, all-photonic quantum repeater protocol allows us to implement the adaptive Bell measurement in a 'time-reversed' manner (called the TRA Bell measurement), by replacing the quantum memories by a photonic graph state*7 with quantum entanglement (Fig. 2). For instance, to perform quantum communication efficiently by using an all-photonic quantum repeater located in the middle of optical fibre links between two users A and B, the users A and B begin by generating quantum entanglement between their own quantum systems and photons, and they then send the photons through optical fibres to the all-photonic quantum repeater. In the repeater, the photonic graph state is generated at the timing of arrival of the photons and measured with the photons by an interferometric photon detection. This TRA Bell measurement at the repeater node, if this works, should work as the quantum teleportation of the survived photon into a photon in the graph state (Fig. 3), without any disturbance of lost photons (Fig. 2). The research group in Osaka University generated a three-photon graph state and realized this loss-tolerant quantum teleportation (Fig. 3) in the lab, as a demonstration of the TRA Bell measurement for all-photonic quantum repeaters.

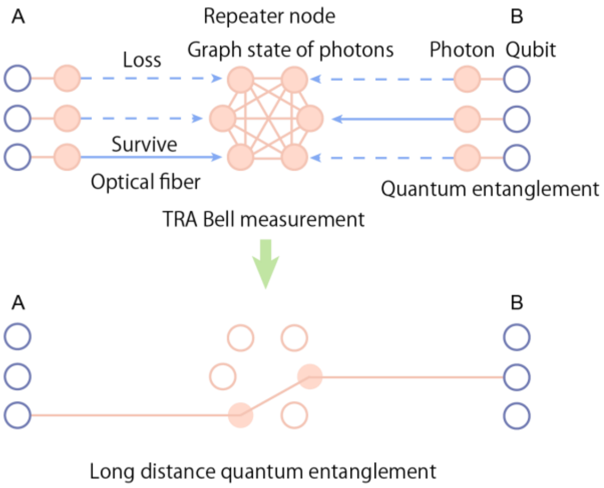

Fig. 2: Concept of all-photonic quantum repeater.

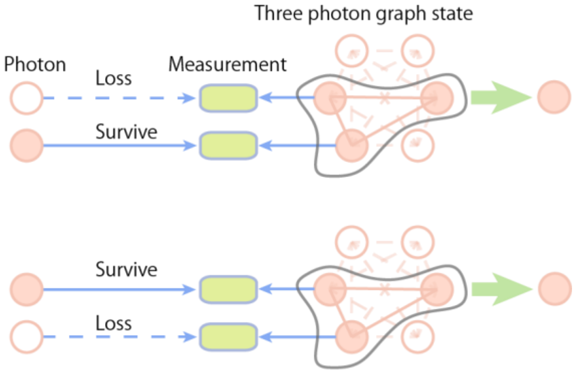

Fig. 3: TRA Bell measurement of our experiment. The quantum state of the survived photon is teleported to the rest of the photons in the graph state, realizing a loss-tolerant quantum teleportation.

❖ Future prospects

In this experiment, the researchers have demonstrated, for the first time, an essential element of quantum repeaters, namely—the adaptive Bell measurement, with its time-reversed implementation of the all-photonic quantum repeater protocol. This shows that the all-photonic repeater approach has a promising advantage compared to the other approaches with matter quantum memories for building a worldwide quantum internet with secure, fast, and low-energy consumption properties. The next steps towards the worldwide quantum internet with the all-photonic repeater are developments of large-scale graph-state photon generators and ultra-low loss photonic circuits enabling the 'time reversal' of adaptive Bell measurement for a large number of photons.

❖ Notices

This research result is published in the journal *Nature Communications*, at 10:00 London time (GMT) on 28th January, 2019, with the following detail:

Title： Experimental time-reversed adaptive Bell measurement towards all-photonic quantum repeaters
Authors： Yasushi Hasegawa, Rikizo Ikuta, Nobuyuki Matsuda, Kiyoshi Tamaki, Hoi-Kwong Lo, Takashi Yamamoto, Koji Azuma and Nobuyuki Imoto
DOI: 10.1038/s41467-018-08099-5

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❖ Glossary

*1 All-photonic quantum repeaters [http://www.ntt.co.jp/news2015/1504/150415a.html]

Quantum repeater protocol that is implementable by using only optical devices such as linear optical elements, single-photon sources, photon detectors and active feedforward techniques, in contrast to conventional quantum repeater schemes that necessitate not only optical devices but also matter quantum memories. Irrespectively of the conventional approach or the all-photonic one, quantum repeaters are necessary for achieving long-distance communication over optical fibres.

*2 Quantum internet

In the field of quantum information, a 'quantum internet' describes a global quantum-communication network which enables us to exchange 'quantum' information—which is represented by quantum superposition states—among arbitrary information-processing devices all over the world.

*3 Matter quantum memory

Quantum memory is the function to store the quantum superposition states for a certain period of time. For instance, in contrast to the memory in the conventional computers that can store both of bit values 0 and 1, quantum memory can keep not only 0 and 1 but also their quantum superposition states. A 'matter quantum memory' is the realization of the quantum memories based on matter such as an atomic ensemble, a single atom, an ion trap, a quantum dot, a superconducting qubit and a nitrogen-vacancy centre in a diamond.

*4 Quantum entanglement

A quantum superposition state of composite systems that can never be expressed by any collection of the descriptions of the subsystems. This is an essential resource for quantum communication and quantum computation. The existence has already been experimentally demonstrated by using photons and atoms.

*5 Adaptive Bell measurement

The 'Bell measurement' is a measurement on a pair of particles to reveal which state of possibly maximally entangled states has been taken by the pair of particles. Each quantum repeater needs to perform the Bell measurement on a pair of particles, on confirming that each particle shares quantum entanglement with other repeater nodes. This Bell measurement performed in an adaptive manner is called 'adaptive' Bell measurement.

*6 All-photonic quantum computer

Quantum computing scheme that is implementable by using only optical devices such as linear optical elements, single-photon sources, photon detectors and active feedforward techniques. This scheme is also known as the KLM scheme, by taking the initials of the inventors, E. Knill, R. Laflamme and G. J. Milburn.

*7 Graph state

An entangled state which is represented by an (undirected) graph composed of nodes and edges. Here the nodes correspond to particles, and the edges connecting nodes represent the existence of quantum entanglement between the corresponding particles.

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