Optical-lattice-clock-network Technology for Gravitational Potential Sensing

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Abstract

Optical lattice clocks have an ultrahigh frequency accuracy that exceeds that of cesium atomic clocks by a few orders of magnitude, enabling quantum sensing of gravitational potential equivalent to an altitude difference of only 1 cm on the Earth's surface. An optical-lattice-clock network, in which multiple optical lattice clocks are interconnected by optical fibers, is expected to become a new infrastructure, such as for a real-time sensing network of crustal movements with 1-cm-level accuracy. In this article, we introduce the elemental technologies comprising an optical-lattice-clock network. We also report on the construction of the ultrahigh-precision optical frequency transmission fiber link in the Tokyo metropolitan area and the experiment to evaluate its transmission stability.

Keywords: optical lattice clock, ultrastable optical frequency distribution, planar-lightwave-circuit-based optical repeater

1. What is an optical lattice clock?

An optical lattice clock refers to the world's most accurate atomic clock[*1], which uses the electronic transition in the optical wavelength region in the neutral atoms captured in a light cage (optical lattice) as a standard for clock ticking (frequency). It was proposed by Professor Hidetoshi Katori of the University of Tokyo (UTokyo) in 2001 [1]. Its time accuracy has reached the level of "1 second difference in 30 billion years." When one considers that general quartz clocks are accurate to "1 second off in a day," one realizes the tremendous accuracy of optical lattice clocks. The accuracy of a clock is generally evaluated by the ratio of frequency uncertainty (Δf) to a clock frequency (f), and the accuracy of a current optical lattice clock is $\Delta f / f \sim 1 \times 10^{-18}$. Our common time is based on the cesium atomic clock, and 1 second in the world is defined as the time which an electron in cesium atom oscillates 9,192,631,770 times. The typical accuracy of cesium atomic clocks today is at the level of $1 \times 10^{-15} – 1 \times 10^{-16}$, or "1 second difference in 30 million years." Optical lattice clocks are already 2–3 orders of magnitude more accurate, so they are being studied worldwide as potential candidates for the next-generation definition of the second. The mechanism of an optical lattice clock is shown in **Fig. 1**. The heart of an optical lattice clock is an atom cooled to a very low temperature (–1 mK), trapped in an optical lattice[*2] made at a special wavelength called a magic wavelength. According to

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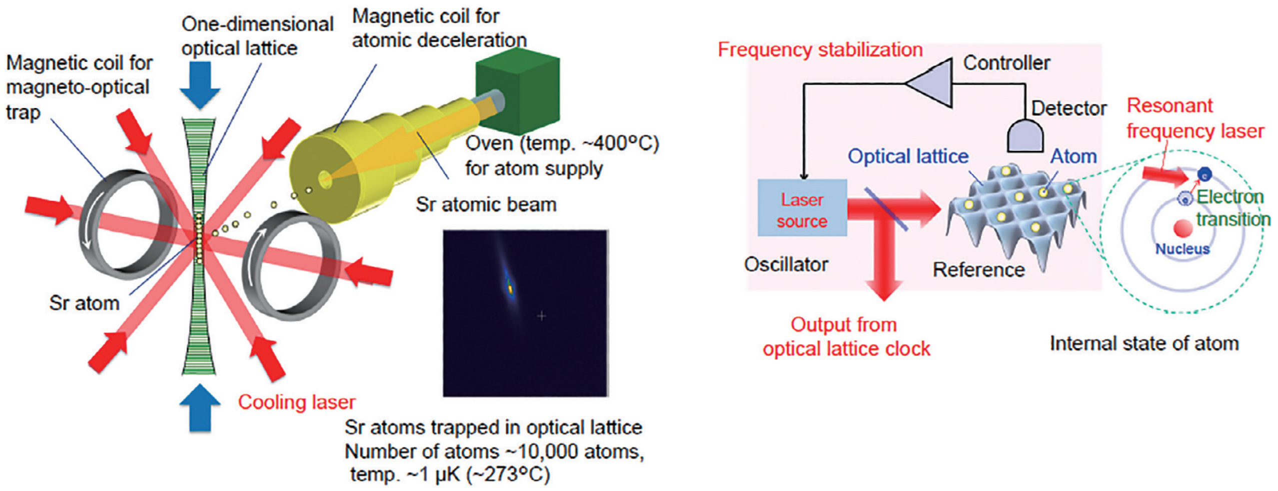
[*1] Atomic clock: A standard frequency generator that uses the resonant absorption frequency of an atom (the property of absorbing and radiating electromagnetic waves of a fixed frequency or its frequency) as a frequency reference. We refer to frequency as a clock in the sense that it is equivalent to a time reference rather than being the inverse of time. The definition of seconds in the SI (International System of Units) unit system also uses an atomic clock based on this principle.

[*2] Optical lattice: A periodic electronic potential is formed by creating a standing wave by the light of an opposing laser. We can arrange laser-cooled atoms in a lattice with this periodic light-induced potential.



(a) Capture atoms with an optical lattice. A beam of atoms is ejected into a vacuum at high temperatures (about 640 K) to be slowed and cooled with a laser. Magnetic fields are also used to gather about 100,000 atoms in one place then trap each atom in an optical lattice, arranging about 10,000 atoms well apart from each other. The photo shows an example of a Sr atom.

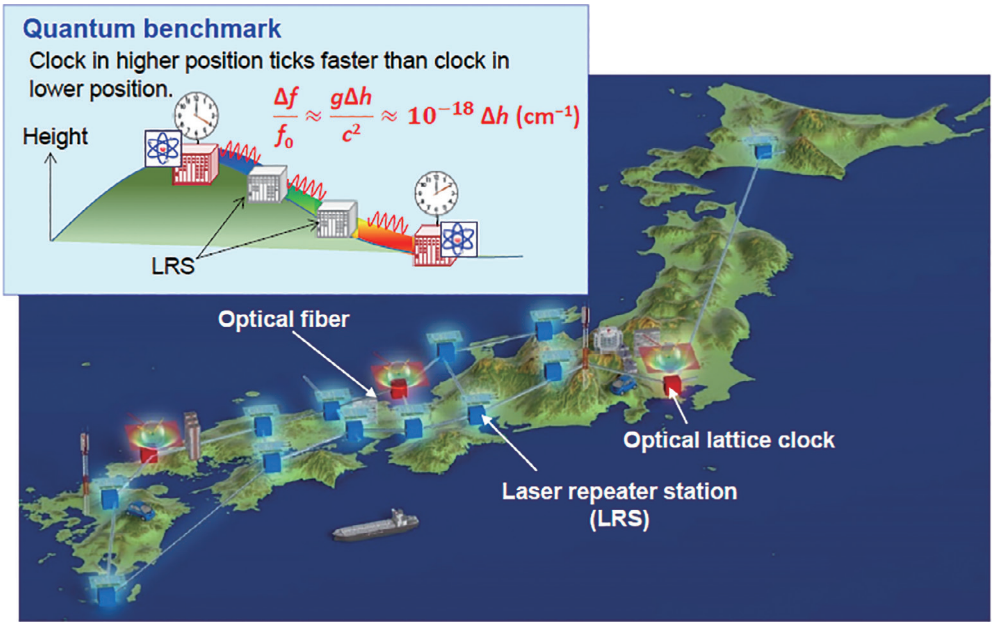
(b) Clock-frequency reading. The frequency of the laser source is stabilized by matching it exactly to the resonant frequency (clock frequency) of the atoms caught in the optical lattice. The figure is drawn as a two-dimensional optical lattice for clarity.

Fig. 1. How an optical lattice clock works.

quantum mechanics, the electrons in an atom absorb electromagnetic waves only at a specific frequency called the resonance frequency (electronic transition). An optical lattice clock enables us to read the resonance frequency by making the frequency of a laser oscillator copy (stabilize) to exactly match this resonant frequency. For example, in the case of strontium (Sr), the most commonly used atom, the resonant frequency is 429 228 004 229 873.0 Hz, roughly equivalent to 698 nm in wavelength. This resonant frequency is extremely accurate and can become the frequency standard when we assume no interaction with the various environments surrounding the atom (temperature, density, electric, magnetic fields, etc.). However, the resonant frequency is easily affected, and environmental fluctuations cause it to fluctuate from the value of the frequency that would be expected if it were not affected by the environment at all. The optical lattice is designed to minimize the effects of the environment by creating electronic potential on the basis of the interference of light and catching each atom cooled to extremely low temperatures. The most outstanding feature of optical lattice clocks is the ability to accurately read the resonant frequency of atoms in a short period by simultaneously measuring many atoms with reduced environmental fluctuations.

2. Expectations for relativistic geodesy by networking optical lattice clocks

According to Einstein's general theory of relativity, when one compares two clocks placed at different heights, the higher clock ticks faster (with higher frequencies) due to the effect of Earth's gravitational potential. Using this principle, a network that enables altitude-difference measurement using relativistic effects (relativistic geodesy) is attracting attention as an application of new ultrahigh-precision clocks. This network will become possible by installing many optical lattice clocks in multiple remote locations nationwide and connecting them via optical fibers and measuring their frequency differences remotely (**Fig. 2**). In fact, the relativistic effect on this clock is well known in conventional atomic clocks. For example, an atomic clock mounted on a satellite orbiting at an altitude of 20,000 km has a frequency about 10^{-10} higher than the Earth's surface because the Earth's gravitational potential is larger than that of the Earth's surface. Optical lattice clocks with much improved accuracy compared with conventional atomic clocks have made it possible to detect relativistic effects arising from slight differences in gravitational potential (differences in height) at the surface of the Earth. Relativistic effects that appear



According to Einstein's theory of general relativity, height shift of an atomic clock of 1 cm causes fractional frequency shift of 1×10^{-18}. Optical lattice clocks connected by an optical-fiber network will provide a space-time information infrastructure based on gravitational-potential measurement.

Fig. 2. Relativistic geodesy with a nationwide optical-lattice-clock network.

only on the enormous spatial scale of space, such as outer space, can now be recognized as everyday effects via optical lattice clocks. This is a revolutionized aspect of such clocks. An optical lattice clock with a frequency accuracy of 1×10^{-18}, which is currently the most accurate in the world, has a detectable gravitational potential equivalent to an elevation difference of approximately 1 cm [2]. If the elevation of each area is constantly monitored with an accuracy of 1 cm using an optical-lattice-clock network, we can expect to expand the role of optical-fiber networks into a new infrastructure, such as a type of benchmark based on gravitational-potential measurements (quantum benchmark) and long-term monitoring of crustal movements. Not only will it be possible to detect altitude-difference measurements with an accuracy of 1 cm, which is difficult with the current geodetic accuracy of the Global Navigation Satellite System (GNSS), but it may also be applicable to long-term monitoring of the movement of massive underground materials, such as magma in volcanoes, which must greatly affect the gravitational potential. It goes without saying that optical-lattice-clock networks play a role in precise frequency-reference delivery, such as what the current GNSS offers, as well as applications such as quantum sensing. If we think back on the fact that the frequencies provided by optical-lattice-clock networks are in the optical domain, they can also be an extremely accurate optical-wavelength reference. If the backbone is an infrastructure capable of synchronizing timing and wavelengths with ultrahigh precision, it is expected to be a platform that encourages development of new optical-communication architectures as well as contributes to current wavelength-division-multiplexing communications.

3. Ultrahigh-precision optical-frequency-transmission device (repeater)

Optical-lattice-clock networks require multiple optical lattice clocks to be connected by optical fibers and their frequency differences measured, but optical fibers are noisy media for transmitting such ultraprecise optical-frequency standards. Optical fiber is always affected by various noise, such as stretching of the fiber due to daily temperature changes and vibrations derived from the surrounding environment, which deteriorates the accuracy of the transmitted optical frequency. Amplifier devices, such as fiber

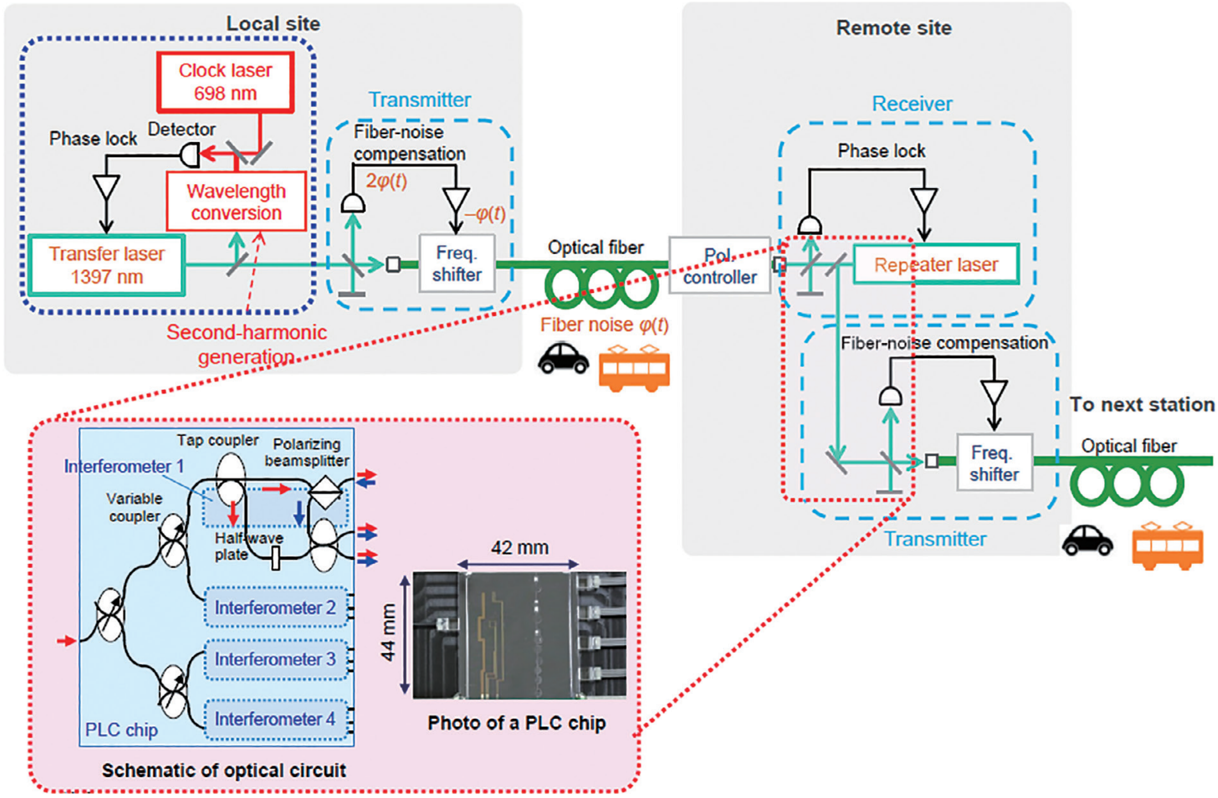


Fig. 3. Optical frequency transmission based on LRS with planar lightwave circuit (PLC).

amplifiers, which are usually used in an optical communication system, are also difficult to use because they can degrade frequency accuracy. An ultrahigh-precision optical-frequency transmission and relay device (repeater) compensates for the noise caused by fiber transmission, maintains accuracy, recovers the propagation loss associated with fiber transmission, and transmits and relays the signal to remote locations (**Fig. 3**). The repeater combines the fiber-noise-compensation function and relay function into a single device, which transmits the fiber-noise-compensated optical frequency to the next section. By the repetitive (cascade) connection of fiber-noise compensation, the optical frequency can be transmitted to a remote location with as little degradation in accuracy as possible. The transmission wavelength of the ultrahigh-precision optical frequency was 1397 nm, which is exactly 2 times the wavelength of 698 nm and corresponds to the resonance frequency of a Sr optical lattice clock. Because of the sub-harmonic relationship, it is possible to convert the optical-frequency reference of a Sr optical lattice clock into a wavelength band capable of fiber transmission with a simple configuration using a single wavelength-conversion device [3].

The most important component in the repeater is an optical interferometer, which achieves two main functions of the repeater. One is fiber-noise cancellation, which compensates for the fiber noise by interfering with the source light and the same fiber being sent back in the opposite direction from the receiver after fiber transmission, detecting the frequency noise coming from the transmitted fiber, and adding the noise in antiphase to that of the source light. The other function is frequency-coherent relaying, in which the frequency accuracy is copied to the transmitting laser by interfering with the ultrahigh-precision optical frequency one wants to copy with the transmitting laser, detecting the frequency difference between the two, and controlling the frequency of the transmitting laser by feedback. Optical interferometers used in conventional repeaters consist of spatial optics and fiber couplers, but there is a problem in that the optical interferometers cannot eliminate interferometer noise. Therefore, the use of a differential detection Mach-Zehnder interferometer based on a quartz-based planar lightwave circuit (PLC)[*3] developed by NTT Device Technology Laboratories has resulted in a smaller repeater and improved stability and detection sensitivity. By building an interference circuit in the optical chip with a precisely designed optical-path length, it is resistant to environmental fluctuations, such as temperature, and has succeeded in reducing noise from the optical interferometer. Differential detection of optical-interference signals is also possible by using the optical interferometer's differential output of light to improve detection sensitivity.

4. Construction of ultrahigh-precision optical-frequency-transmission fiber link in metropolitan area

Toward the implementation of this optical-lattice-clock network, NTT Basic Research Laboratories has been conducting field demonstrations since 2015 in collaboration with the Katori Laboratory in UTokyo, RIKEN, and NTT EAST. Optical lattice clocks with the world's highest accuracy level can currently achieve a frequency stability of 1×10^{-18} with an averaging time (data integration) of more than 10,000 seconds. Therefore, to transmit an optical lattice clock without degrading its stability, optical-fiber transmission must reach 18 digits of frequency stability in less than 10,000 seconds of measurement time. The scalability of the fiber distance is also an important factor if we assume that we will expand such an optical-lattice-clock network on a nationwide scale. Using the repeater developed by NTT, we constructed an ultrahigh-precision optical-frequency-transmission fiber link for a demonstration experiment involving connecting multiple relay stations (telecommunications offices) from RIKEN's Wako location (in Saitama Prefecture) to the NTT Atsugi R&D Center (in Kanagawa Prefecture) via the UTokyo's Hongo campus (in Tokyo) (**Fig. 4**). This is a demonstration of an optical-lattice-clock network within an area corresponding to one region consisting of several prefectures in Japan. The relay station was equipped with a compact remote-controllable repeater system that can be set in a 19-inch-rack unit. The transmission accuracy was evaluated using a 240-km-long loop network in which an ultranarrow linewidth laser was transmitted from Wako to Atsugi via the repeater at UTokyo then transmitted back to UTokyo through the other optical fiber installed on the same path. At UTokyo, we measured the frequency stability[*4] by detecting the interference between the optical frequencies transmitted to Atsugi and those returned by the loop network. By measuring the frequency difference between the transmitted light and the light returning through the fiber network, we can assess the noise (how much it degrades frequency stability) that originates from the transmitted fiber. We demonstrated transmission with frequency stability and accuracy of 3×10^{-16} for 1-second averaging time and 1×10^{-18} for 2600-second averaging time [4]. This frequency-transmission stability is an achievement that will lead to future application of relativistic geodesy with 1-cm accuracy, which does not deteriorate the accuracy of the world's most accurate optical lattice clock. Previously, UTokyo and RIKEN carried out relativistic geodetic experiments between Hongo and Wako by comparing the frequencies of 2 optical lattice clocks with 30 km of non-relaying fiber transmission. They demonstrated the principle of remote altitude difference measurement with accuracy of several centimeters [5]. Since the transmission distance without relaying is roughly limited up to 100 km due to the fiber-propagation loss, the cascade-relaying method through repeaters we demonstrated will enable us to extend to a regional level of several hundred kilometers or national level of several thousand kilometers with ultrahigh precision.

5. Summary and future outlook

We introduced an ultrahigh-precision transmission technology of an optical frequency standard, which enables optical-fiber transmission over 200 km without deteriorating the accuracy of the world's highest-performance optical lattice clock. We plan to conduct frequency-comparison experiments on optical lattice clocks installed at Wako and Atsugi using the fiber link we constructed. This will enable the demonstration of relativistic geodesy to detect height differences with several-centimeter-accuracy between remote locations on the 200-km scale. On the assumption of a nationwide optical-lattice-clock

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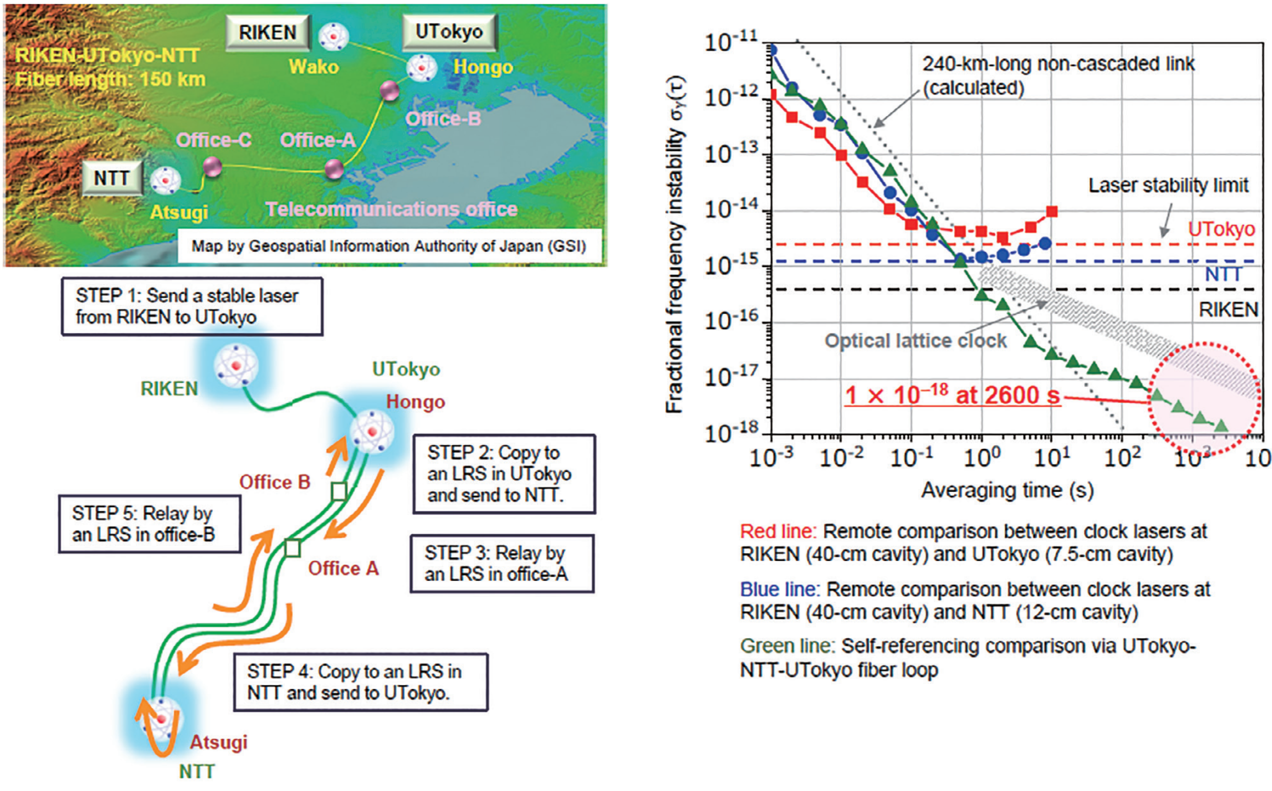
[*3] Quartz-based PLC: This optical waveguide technology, which has been put into practical use by NTT, enables optical waveguides to be manufactured in a process similar to large-scale integrated circuits and integration of various interferometers. PLCs are superior for mass production because of their ability to automate manufacturing and are highly effective in reducing costs during mass production. They are also characterized by low loss and high reliability because they can form waveguides with the same glass materials as optical fibers.

[*4] Frequency stability: A measure of frequency precision and defined as how constant the frequency is for a specified time interval.



(a) 240-km-long link stability is estimated by measuring a beat signal at UTokyo.

(b) Frequency instabilities measured with UTokyo-NTT fiber link

Fig. 4. Optical frequency transmission experiment in Tokyo area.

network, we plan to develop repeaters capable of stable operation with more relays and extend this ultrahigh-precision optical-frequency-standard fiber-transmission technology to the 1000-km scale.

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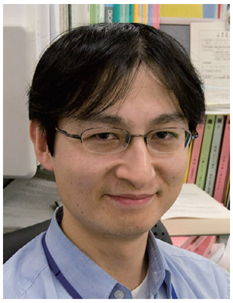

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