National electrical standards supporting international competition of Japanese manufacturing industries

— Realization of a new capacitance standard and its traceability system —

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A capacitor or a condenser is one of the most basic electrical devices and is used in various electrical equipments. Recently the electrical equipment industry has been requesting the quality of capacitors to be compatible with international standards; among other things, it is strongly demanded that the traceability of a capacitance standard should be consistent with the national standards. To respond to this need from industry, we have developed a new national standard of capacitance based on the quantized Hall resistance and also established its traceability system in cooperation with the accredited calibration businesses. A remote calibration system of capacitance has also been developed to disseminate the standard quickly and to reduce calibration costs.

Keywords : Capacitance, condenser, electrical standard, traceability, remote calibration

1 Introduction

The manufacturing industry for electronic parts and modules including the laminated ceramic capacitor, chip inductor, EMI filter, and thin-film resistor element is one of the major industries in Japan. For example, capacitor alone has estimated market scale of 800 billion to one trillion yen. The demand for capacitors is increasing due to the increased and diversified performance of the digital home appliances such as the flat panel television, cell phones, and personal computers, as well as increased use of electronic elements in automobiles. Moreover, there is a high expectation for high-volume battery capacitor as the next-generation energy device, and further demands are expected in the environment and energy fields[1]. Currently, the global share of Japanese electronic parts industry for capacitors is estimated at about 70 %, but the shares of other Asian electrical companies are rapidly increasing.

The main customers of the electronic parts companies, or the main supply destination of the electronic parts, are the major manufacturers of automobile, electrical appliance, or communication device industries. These industries are demanding increased reliability of electronic parts and modules from the perspective of safety, security, and energy saving. At the same time, there is a strong demand for compatibility with the international standards such as the ISO/TS 16949 (international standard for the quality management system of the automobile industry) and ISO/IEC 17025 (international standard for the capability of the testing and calibration laboratories). The establishment of metrological traceability to the national standard is mandatory. For the Japanese electronic parts companies, to meet the demands of their customers, the establishment of measurement traceability and the compatibility to international standard for the testing device in their manufacture line are pressing issues.

To respond to the demands of the Japanese industry, the National Institute of Advanced Industrial Science and Technology (AIST) is developing the national standards of various electric quantities such as voltage and resistance, establishing these as standards with international compatibility through international comparisons, and is building a system for widely disseminating the metrology standards to the site of production of the Japanese industries through the Japanese calibration laboratories. The quantities of impedance such as capacitance, inductance, and AC resistance are the most fundamental physical quantities among many electric quantities. However, with the enhanced performance of electronic devices as well as the improved performance and increased electronic parts in automobiles, the demand for highly precise standards, particularly for capacitors, has risen in the last ten years. Therefore, the standard setting and realization of the capacitor or the capacitance standard were reviewed starting from zero, and R&D was conducted to establish a new capacitance standard and to build the metrological traceability system.

By disseminating the world's highest electrical standards, including the capacitance standard to the Japanese electronic parts companies, the metrological traceability can be guaranteed for every electronic part. We wish to support the global competition and the technological development of the Japanese electronic parts industry as well as the Japanese core industries such as electrical, communication, and automobile industries that are the destination of these

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electronic parts. We hope to contribute in strengthening the international competition power of the industries.

2 Scenario

2.1 Establishment of the development goal of the national standard

In developing a new national standard, it is necessary to establish the goal of the development, such as "What level of uncertainty (precision) should the national standard for the newly developed capacitance target?" and "What is the expected secondary measurement standard that will be the subject of calibration?" At the time we started the development, the mainly used secondary measurement standard capacitors, which were calibrated from the national standard (primary measurement standard), were air capacitors or mica capacitors. These were used because the temperature coefficients were small or the devices themselves were small and easy to handle. They were used widely in the corporate standard labs, but the expected uncertainly was of 1 ppm (1 μF/F) level. The electronic parts companies or the capacitance measuring instrument manufacturers that demanded high-precision capacitance standard owned the fused-silica capacitor that had higher precision and stability than the air capacitor, and wanted standard for this type of capacitors. The fused-silica capacitors were capable of achieving uncertainty of 0.1 ppm level. Therefore, we set the fused-silica capacitor as the subject of calibration and developed the national standard for capacitance.

The developed capacitance standard was compared with the standards of the national metrology institutes (NMI) of other countries to check its equivalency, and then to establish the international compatibility. Surveying the uncertainties of the capacitance standards realized at the NMIs of countries that realized the world's top-level capacitance standard, specifically, the National Institute of Science and Technology (NIST, USA), Physikalisch-Technische Bundesanstalt (PTB, Germany), National Measurement Institute of Australia (NMIA, Australia), and Laboratoire National de Métrologie et d'Essais (LNE, France), it was found that these NMIs have established the standard of uncertainly of 0.1 ppm or less[2]-[5]. We decided that the world's top-level standard must be achieved in assuming a highly precise and stable fused-silica capacitor as a calibration subject (secondary measurement standard), and to support the global competition of the Japanese industries. Therefore, we set the development goal: "the establishment of a national standard with standard uncertainty of 0.1 ppm or less".

2.2 Scenario for the dissemination of standard to industrial sites

To disseminate the capacitance standard to the manufacturers' production site and to build the metrological traceability system, we believe the role of the private calibration laboratories is mandatory. Currently, many NMIs around the world develop and organize standards required by industry and provide wide-ranging calibration services. (For example, the NIST and PTB provide about 330 types of electrical standards, while Standards and Calibration Laboratory [SCL, Hong Kong] provides about 200 calibration services[6].) However, it is not necessarily the best policy for AIST to organize and provide the standards for all ranges to meet the demands of industries. This is because there are several highly capable calibration labs and precision machine manufacturers in Japan compared to other countries. In building the metrological traceability system, if it is possible to maximize the calibration abilities of the cooperating laboratories in Japan, it will be possible to realize the stable dissemination of standards to the far corners of the industrial sites. At the same time, it will enable AIST to slim down its function and to allocate the resources efficiently. With this background, a standard provision system was considered for the capacitance standard and is shown in Fig. 1.

In this system, AIST develops and establishes the national standard for the basic range and provides this to the Japanese calibration labs. The calibration labs expand the calibration range based on the disseminated basic range standard, and then disseminate them to the industrial sites. In this case, the role of AIST is limited to regularly disseminating the highly precise basic range standard to the upper-tier calibration labs, and this enables simplifying its calibration work. Also, by limiting the range of the standards provided, the AIST resources can be focused and concentrated, and this in turn enables achieving higher precision and efficiency of the calibration devices. The method for disseminating

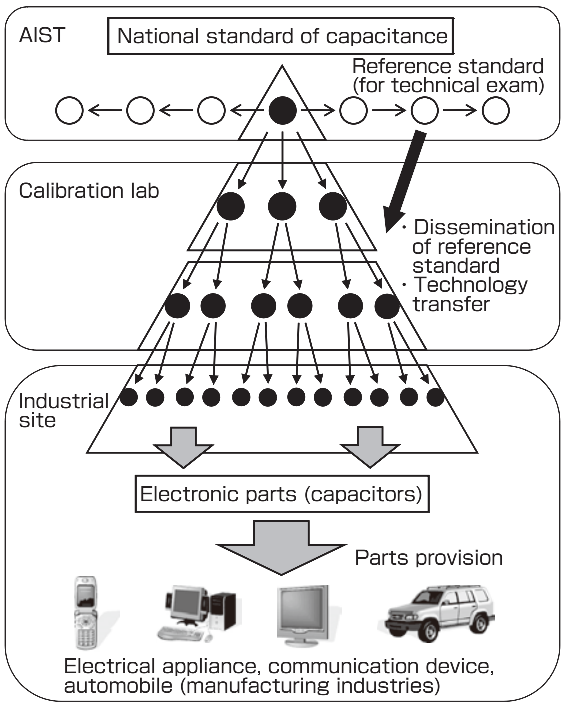

Fig. 1 Scenario for the system of capacitance standard provision

the standards is based on the Japan Calibration Service System (JCSS) of the Measurement Law. This builds the hierarchy of standard dissemination as shown in Fig. 1. The high-precision basic range national standard of AIST is expanded by the calibration labs of each tier, and is disseminated promptly to the site of production. Specifically, AIST develops and organizes the 10 pF, 100 pF and 1000 pF capacitance standards, and disseminates these to the upper-tier calibration labs. The upper-tier calibration labs may, for example, expand the calibration range to 1 μF based on the 10 pF standard, and this is provided to the lower-tier calibration labs. The lower-tier calibration labs may further expand the calibration range to provide the capacitance standard to the sites of production. By building this system, the necessary range of capacitance standard can be disseminated to the manufacturers' site of production when needed, while maintaining the link to the national standard. This means that the metrological traceability system of the measurement device or the capacitor at the site of production to the national standard can be established efficiently.

In building this standard dissemination system, the role of calibration labs at each tier, particularly the role of uppermost-tier calibration labs, is extremely important. Therefore, AIST must not only develop and disseminate the national standard, but also provide support to improve the technical skills of the calibration labs. Also, a standard (reference standard for skill examination) will be necessary to evaluate and judge the technical skills. This is because if the calibration lab expands, for example, to 1μF or 10 μF based on the 10 pF national standard, it is necessary to check whether the expanded result is correct or wrong. Therefore, as shown in Fig. 1, the range of the capacitance standard can be expanded to some extent at AIST (i.e. expansion to 1 μF or 10 μF based on 10 pF, 100 pF and 1000 pF), and these are used as reference standards to check the techniques of the calibration labs. To plan and organize all the standards that must be developed, the standard organization plan is created for each fiscal year as shown in table 1. The resource allotment is planned according to this plan to develop and realize the standards. Since the understanding and cooperation of the Japanese calibration labs are necessary to achieve this system, we set out to build consensus by actively exchanging opinions with industry at committees and research presentations for standards.

3 Development of the capacitance standard

3.1 Selection of the method

Two methods have been recognized in the world as ways to realize the capacitance standard. One is the method of using the specially shaped capacitor called the cross capacitor. As shown in Fig. 2, according to A.M. Thompson and D.G. Lampard, if the four electrode rods arranged parallel to each other, and the value per unit length of the capacitance (cross capacitance) between the two sets of opposing electrodes are set as C_{12} and C_{34}, the average values of C_{12} and C_{34} can be expressed in the following equation[7]:

Table 1 Organization plan for the capacitance standard

Capacitance to be disseminated	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
10 pF		○								
100 pF	○									
1000 pF		○								
0.01 μF				○						
0.1 μF				○						
1 μF				○						
10 μF						○				
100 μF									○	
1000 μF										○

$$(C_{12}+C_{34}) / 2 = (\varepsilon_0 \ln 2) / \pi \qquad (1)$$

As seen from the above equation, the average value of the cross capacitance per unit length is dependent only on the permittivity ε_0 between the electrodes. If the entire cross capacitor is placed in a vacuum, the cross capacitance per unit length will be 1.953549043… pF, and this is not dependent on the shape of the electrode. This means that if the length of the electrode rod is determined accurately, the capacitance can be determined by the length standard of the cross capacitor. However, the condition that makes equation (1) valid assumes that the four electrode rods are infinitely long. Therefore, the capacitance for unit length of electrode rod of infinite length is expressed by equation (1). Therefore, to actually realize the cross capacitor, it is necessary to insert a separate guard electrode between the four electrodes. The area where the guard electrode is inserted will have capacitance zero. When the guard electrode is moved in this state, the capacitance increases or decreases in accordance to the distance transferred. If the cross capacitance for the transferred distance of the guard electrode is calculated, it will follow equation (1). Many NMIs have established the capacitance standard using this method[2]-[5]. However to fabricate the actual cross capacitor, the precise machining of the electrode rods is extremely important. The surface roughness and the degree of parallelness of the electrode rods will directly affect the uncertainty

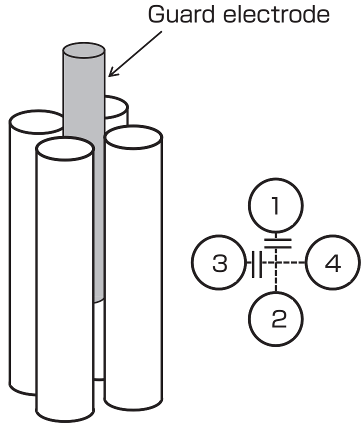

Fig. 2 Cross capacitor

of the cross capacitance. Also, the capacitance measurement by cross capacitor requires experience and skill, and it is not easy to realize the standard of 0.1 ppm or less using this method. While the leading countries of cross capacitor, NMIA (Australia), NIST (USA), PTB (Germany), and LNE (France) have realized the standard for 0.1 ppm or less using this method, the uncertainties at other NMIs are over 0.1 ppm. Also, the Electrotechnical Laboratory (currently AIST) had fabricated and realized the cross capacitor before, but has not achieved uncertainty 0.1 ppm or below[8].

Another method for realizing the capacitance standard is the method using the resistance standard based on the quantized Hall resistance, as shown in Fig. 3. Since 1990, it has been agreed worldwide that the standard for DC resistance will be determined by the quantized Hall resistance. The Electrotechnical Laboratory (current AIST) has disseminated the resistance standard based on the quantized Hall resistance, by organizing and developing the quantized Hall resistance standard according to the agreement (Recommendation of the 77th Comité International des Poids et Mesures [CIPM], 1988)[9]. If the origin of the standard is set in the quantum effect, same results should be obtained any time, anywhere, and by anyone. Particularly, the equation for expressing the quantum Hall effect is shown by equation (2). As it can be seen from the equation, absolutely no other standards are necessary to determine the quantized Hall resistance R_H (h is the Planck's constant, e is the elementary charge of electron, and i is the integer that represents the degree of quantization).

$$R_H(i) = h / ie^2 \tag{2}$$

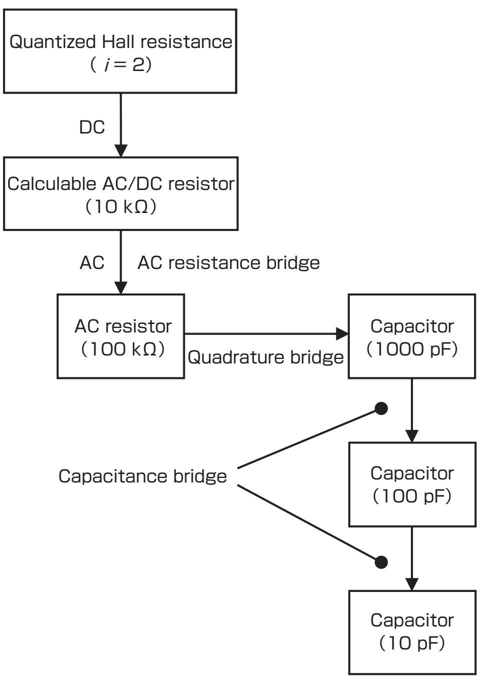

Fig. 3 Capacitance standard based on quantized Hall resistance

This is an advantage that differs greatly from the cross capacitor method where the length standard will always be required to determine the capacitance no matter how precisely the electrode rods are fabricated. Also, as mentioned above, the quantized Hall resistance is the origin of the DC resistance standard. If it is possible to derive the capacitance from the quantized Hall resistance, then sharing and efficient use of the devices can be achieved, and the maintenance and management will be easier after developing the standard. Therefore, we decided to employ the method of deriving the capacitance standard from the quantized Hall resistance.

3.2 Development of the new method to respond to the demands

To derive the capacitance from the quantized Hall resistance, various bridge circuit and special resistors are necessary, as shown in Fig. 3. Specifically, these include the AC resistance bridge, quadrature bridge, capacitance bridge, and a specially shaped resistor that can calculate the AC/DC difference. The capacitance can be derived from the quantized Hall resistance by developing these devices at high precision, and then using them to sequentially measure from resistance to capacitance. In this series of measurements, the quadrature bridge that converts the resistance to capacitance is particularly important in determining the final uncertainty of the capacitance standard. Figure 4 shows the circuit configuration

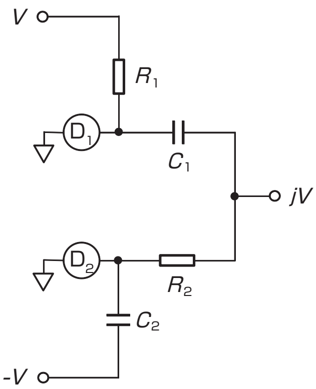

Fig. 4 Quadrature bridge

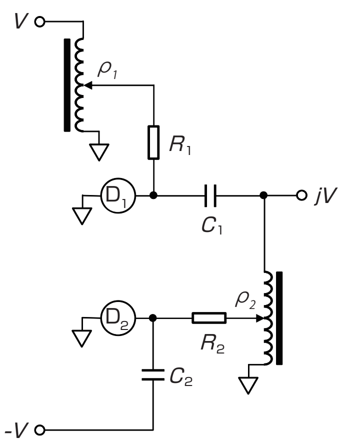

Fig. 5 Multi-frequency quadrature bridge

of the quadrature bridge. From this diagram, the equilibrium condition of the quadrature bridge is as follows:

$$\omega^2 C_1 C_2 R_1 R_2 = 1 \qquad (3)$$

Here, ω is angular frequency, C_1 and C_2 are capacitances, and R_1 and R_2 are resistances. In determining the capacitance based on the resistance of the quadrature bridge, the bridge balance frequency is determined uniquely. (As it is apparent from equation (3), when the resistances R_1 and R_2 and the capacitances C_1 and C_2 are set as fixed values, there will be only one bridge balance frequency ω.) Therefore, the capacitance derived from the quantized Hall resistance is limited to the value at a certain frequency. (Normally, to attain $C_1 = C_2 = 1000$ pF and $R_1 = R_2 = 100$ kΩ, the equilibrium frequency is ω = 104 rad/s, or about 1.592 kHz.) This is a disadvantage against the capacitance standard using the cross capacitor (since, in principle, the cross capacitor is not dependent on frequency).

As shown in Fig. 1, the direct supply destination of the developed capacitance standard is the upper-tier calibration labs that disseminate high-precision calibration service. We conducted a survey for the needed calibration frequency of the capacitance standard of the measuring instrument manufacturers and private calibration labs that were

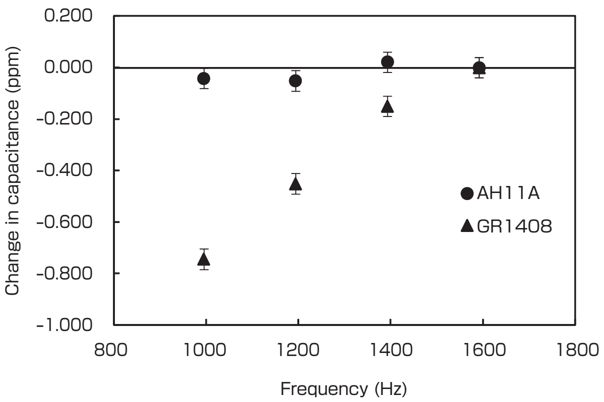

Fig. 6 Frequency characteristic of the fused silica standard capacitor

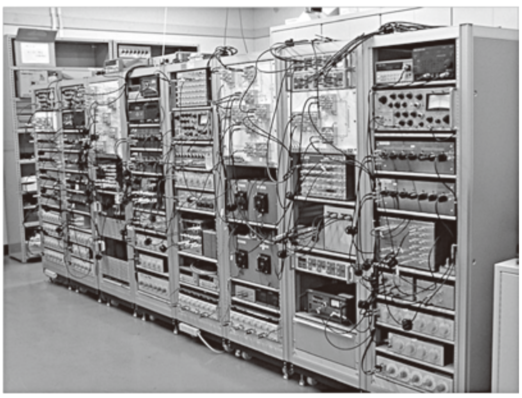

Fig. 7 Capacitance standard based on quantized Hall resistance (national standard)

candidates of upper-tier calibration labs, and found that "the request is calibration at 1 kHz". However, using the circuit shown in Fig. 4, the capacitance derived from the quantized Hall resistance is limited to the value of 1.592 kHz. There was a general thinking that the difference between 1 kHz and 1.592 kHz, or 592 kHz, could be ignored, but we decided to satisfy the industrial demands before we started to disseminate the standard. It was necessary to measure and evaluate the frequency characteristics around 1 kHz for the fused silica standard capacitor that will be the subject of calibration. Revisions were made to the circuit in Fig. 4, and we devised a quadrature bridge with new circuit configuration where the bridge balance frequency can be varied. Figure 5 shows the circuit for the multi-frequency quadrature bridge. When two inductive voltage dividers are added to the conventional circuit (Fig. 4), the bridge balance condition of the bridge can be expressed by equation (4).

$$\omega^2 C_1 C_2 R_1 R_2 = \rho_1 \rho_2 \qquad (4)$$

Here, $\rho_1\rho_2$ is the voltage ratio of the newly added inductive voltage dividers. By taking the partial pressure ratio $\rho_1\rho_2$ arbitrary, in principle, the quadrature bridge will reach bridge balance at all frequencies. In practice, the bridge was built by using ρ = n/8 (n = 1, 2, 3, …), and we created a multi-frequency quadrature bridge where the bridge balance frequency was 1.25n/2π kHz[10]. Using this bridge to measure the frequency characteristic of the fused silica capacitor, as shown in Fig. 6, it was found that capacitance change occurred according to the frequency variation around 1 kHz in a certain type of capacitor (GR1408). We obtained new findings that refuted the general thinking of, "there was no frequency dependency between the range 1.592 kHz and 1 kHz in fused silica capacitor"[11]. At the same time, for the AH11A standard capacitor that was assumed to be the major secondary standard, it was confirmed

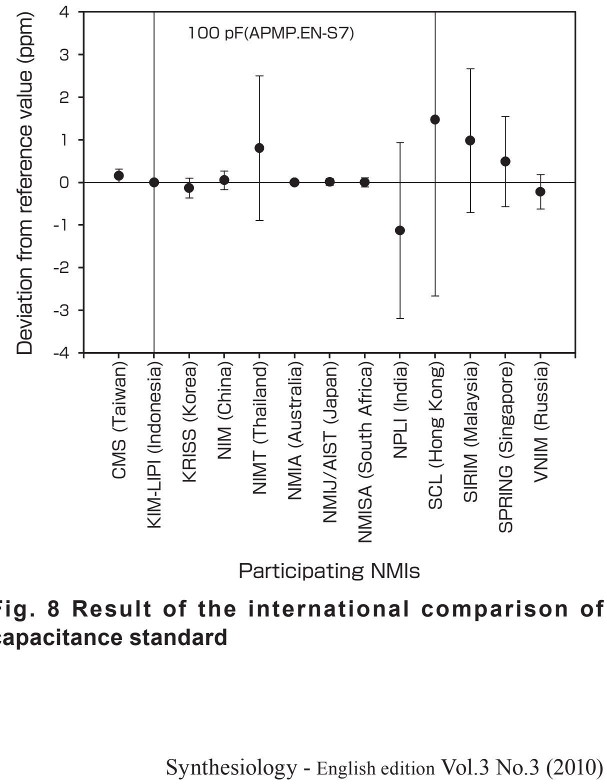

Fig. 8 Result of the international comparison of capacitance standard

that the capacitance change by frequency can be ignored[12]. Therefore, we developed the “capacitance standard based on quantized Hall resistance” that incorporated the new circuit configuration with added variable frequency to the quadrature bridge (Fig. 7). When the uncertainty of the developed capacitance standard was evaluated, the estimated standard uncertainly was 0.04 ppm, and we were able to achieve the goal of 0.1 ppm or less. This result was confirmed in the international comparison (Fig. 8), and after the technological peer review by the specialized researchers of the NMIs of other countries, it was demonstrated that the international equivalency was attained (CMC registration[6]). Currently, the institutes other than AIST that have realized the capacitance standard based on the quantized Hall resistance are National Physical Laboratory (NPL, UK), Center for Measurement Standards (CMS, Taiwan) and the Bureau International des Poids et Mesures (BIPM), but all of them use the conventional circuit as the quadrature bridge.

4 Establishment of the metrological traceability system

4.1 Development of the reference standard for technical review and technology transfer

The capacitance standard developed by AIST is disseminated to the industrial sites based on the standard dissemination system shown in Fig. 1. Also, the metrological traceability system for capacitance is established. However, as mentioned above, the standards provided by AIST are only for 10 pF, 100pF and 1000 pF, while at the sites of production, the capacitance standards for the range from 1 pF to 100 μF are required. Therefore, expansion of the calibration range is necessary at the calibration labs of each tier in Fig. 1. The candidates of calibration labs include the capacitance measuring instrument manufacturers and quality control divisions of the electronic parts companies, and these calibration labs must develop the expansion method on their own using the capacitance standard provided by AIST, and realize and provide the capacitance standard in the range needed at the industrial sites and by the customers. In this case, the calibration labs will undergo the technical review based on JCSS for the technical adequacy of the expansion method. For this review, a reference standard (standard with known value) is necessary to judge whether the expansion result is correct or wrong. For example, when a calibration lab conducts the calibration for 1 μF using a method it developed on its own based on the value for 10 pF provided by AIST, to judge whether the calibration result is right or wrong, a standard for 1 μF with a known value is necessary. Therefore, AIST developed the standards for 0.01 μF, 0.1 μF, 1 μF and 10 μ F (medium-capacitance standard) as reference standards for the technical review, other than the standards for 10 pF, 100 pF and 1000 pF (low-capacitance standard), and disseminated them to the National Institute of Technology and Evaluation (NITE) that conducts the technical review for JCSS. To develop the medium-capacitance standard, the technology where all the measurement systems are coaxial four-port bridge was employed. By doing so, the capacitance could be expanded or the lower impedance could be handled. By employing the coaxial four-port bridge, the influence of the measurement cable could be removed and the effect of the parasitic impedance could be reduced. The developed medium-capacitance expansion system is shown in fig. 9. The uncertainties of the medium-capacitance expansion system were estimated at standard uncertainty of 0.38 ppm for 0.01 μF and standard uncertainty of 2.0 ppm for 10 μF. We hence developed the capacitance expansion system with sufficient precision as the reference standard for technical review[13][14].

To technically support the expansion of the calibration range by the calibration labs, the medium-capacitance expansion technology developed at AIST was transferred to the Japan Electric Meters Inspection Corporation (JEMIC), which is one of the calibration labs[15]. (Specifically, the medium-capacitance expansion system that was the same as the one at AIST was developed at JEMIC through joint research with AIST.) As a result, expansion of the capacitance range using the medium-capacitance expansion system was achieved at JEMIC, which was then accredited as a JCSS calibration lab upon review by NITE. Active technical instructions and advices were given on the analysis method of uncertainty for the range expansion to other calibration labs, and now, there are three JCSS labs (uppermost-tier calibration labs) accredited for the capacitance standard. (For overall electrical standard, currently there are about 50 JCSS accredited labs, and nine labs including the above three are accredited as the uppermost-tier calibration labs.)

4.2 Development of the new dissemination method and analysis of the standard dissemination status

As mentioned earlier, the presence of the calibration labs is indispensable in establishing the metrological traceability system of the capacitance standard. We drafted a scenario for disseminating the national standard from AIST to the

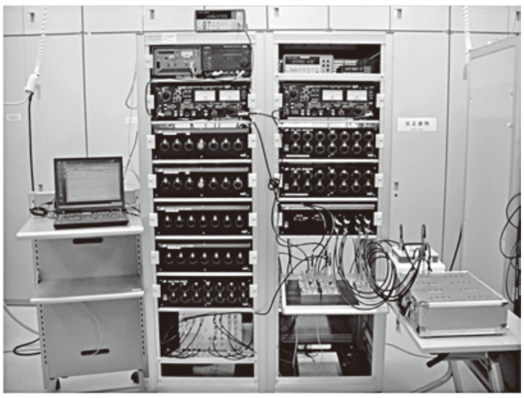

Fig. 9 Medium capacitance expansion system

industrial sites through the calibration labs. In the current situation, the accreditation of the JCSS calibration labs for capacitance is progressing, and the standard dissemination system according to the initial scenario is being realized. However, the sites of production are where the metrological traceability is truly needed, and our goal is achieved only when the demands of the industrial sites are satisfied. Therefore, we thought a survey and analysis of the state of the metrological traceability system at the industrial sites were necessary. We surveyed the demand for standard dissemination system of the industries, and found that with the current dissemination system, it was difficult in terms of time and cost to guarantee the metrological traceability to each and every measuring device at the site of production. In the current system where the measuring device that must be calibrated is transported to the calibration lab for calibration (carry-in calibration), the production line where the measuring device is used must be stopped while the device is being calibrated, and this is not practical for the production line that is normally in operation 24 hours. Also, when all of the several hundred or several thousand measuring instruments used at a site of production were to be calibrated, the calibration fee will be enormous and is not realistic. Therefore, we determined that it was difficult to establish the metrological traceability system to the industrial site according to the initial scenario.

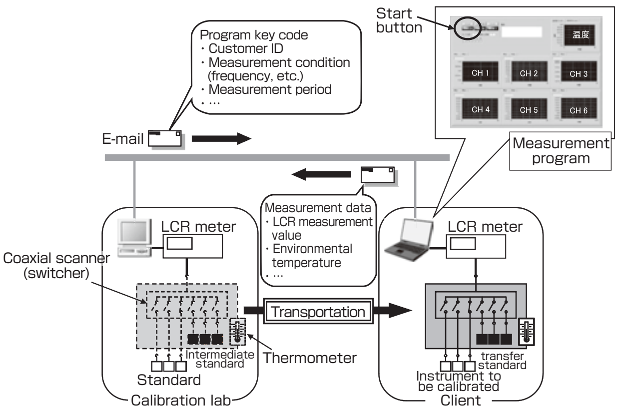

Fig. 10 Conceptual diagram of the remote calibration for capacitance standard

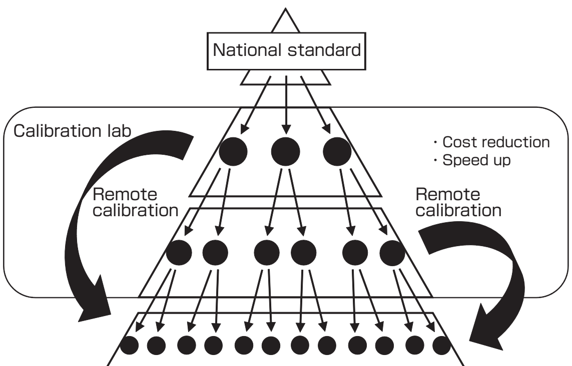

Fig. 11 Quickening the service dissemination by remote calibration and rationalization of the traceability system

Therefore, we conducted an R&D on a remote calibration method as a new dissemination method that may reduce the calibration time and cost[16]-[18]. Figure 10 shows the conceptual diagram for remote calibration of the capacitance standard. This calibration method uses an intermediate standard. Normally, to receive the calibration service, the clients must send or bring their instrument to be calibrated at their own expense and responsibility to the calibration lab. In the remote calibration shown in Fig. 10, the client uses the transfer standard and the measuring device sent by the calibration lab to conduct the measurements necessary for the calibration of the instruments on their own. Specifically, as shown in the figure, the transfer standard that has been previously calibrated by the calibration lab is sent to the client. At the same time, a switching device called the coaxial scanner is also sent. The client connects the commercial LCR meter, personal computer (PC), and the instrument to be calibrated to assemble the (remote) calibration system, starts up the measuring program installed in the PC beforehand, and conducts the measurement. The calibration system and the measurement program are designed to conduct the measurement automatically from beginning to end, and the client does not need any special training or skills. The measurement results obtained by the client are automatically sent to the calibration lab by e-mail. The data is analyzed by the calibration lab, and the result is returned to the client by e-mail. In remote calibration, the client does not have to transport the instrument outside to receive the calibration service. This will eliminate the cost needed for the transportation of the instrument, and can minimize the period during which the instrument cannot be used due to calibration. By incorporating the remote calibration method in the standard dissemination system, it will be possible to disseminate the standard to the sites of production directly from the upper-tier calibration labs, and this will rationalize the metrological traceability system as well as speed up the dissemination (Fig. 11).

The external appearance of the developed remote calibration system is shown in Fig. 12. In developing this system, considering the diffusion to industry and the reduction of the

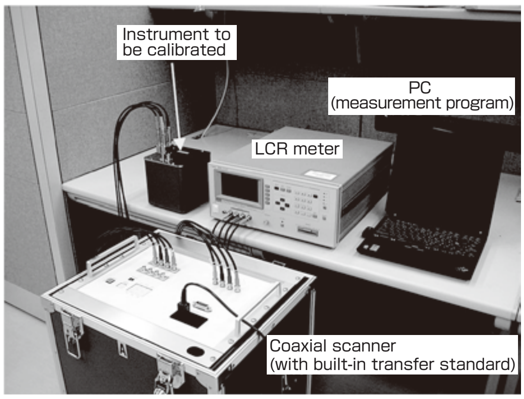

Fig. 12 LCR standard remote calibration system

introductory cost, commercially available measuring devices that were used widely in industry were employed in parts of the calibration system. Also, the system was designed to be used by clients (users) without special knowledge of calibration. For sending and receiving of the data and setting of the measurement conditions, particular care was taken for data protection and security measures to prevent intervention by the user. Also, the system allowed the remote calibration of all impedance standards (LCR standard) including inductance (L), AC resistance (R), and capacitance (C). Figure 13 shows the results of the demonstration experiment of the remote calibration using this system. The results were equivalent to those of the conventional carry-in calibration. Based on these results, we are investigating the practical use of the system, and are currently discussing the introduction of the remote calibration system with a Japanese electronic parts company. There are several thousand inspection meters for LCR parts at the production site of this company, and we expect to be able to provide the metrological traceability guarantee to all measuring devices through remote calibration. Also, active technological transfer and practical use are provided to other companies, to advance the quick dissemination of the capacitance standard to the industrial sites and to enable the establishment of the metrological traceability system.

5 Future issues

A series of R&D were conducted to support the competitive power of the Japanese industry by developing the world's top-level capacitance standard that is internationally compatible, and to establish the metrological traceability system by building the system for disseminating the standard to the industrial sites through the calibration labs. To present, three JCSS calibration labs are registered and accredited, and these labs are capable of conducting calibration in the range of 1 pF ~ 100 μF. Thus the basic standard dissemination system was established. However, to establish the true metrological traceability system, it is necessary to build a system that can disseminate the standards needed at the sites of production quickly and at low cost. As one of the solutions, we considered the remote calibration system, and conducted R&D for the remote calibration system for the impedance standards (LCR standard) including the capacitance standard. While it has been technically demonstrated by experiment to be ready for practical use, to diffuse this system to industry, there are unsolved issues such as cost reduction of the system and the JCSS accreditation of the remote calibration method. However, a system that disseminates the national standard established by AIST to all the corners of industrial sites should be the issue in the future. We shall consider new methods of dissemination as well as the remote calibration method proposed in this paper, and the issue for the future is the establishment of a more efficient and rational metrological traceability system.

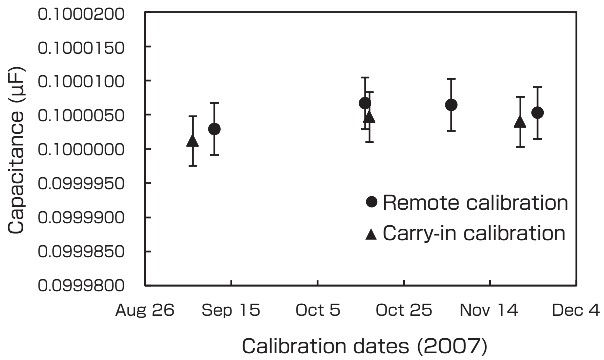

Fig. 13 Experimental results of remote calibration (comparison to carry-in calibration)

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Completed the doctoral course at the Graduate School of Engineering, Doshisha University in March 1994. Doctor (Engineering). Joined the Electrotechnical Laboratory, Agency of Industrial Science and Technology (current AIST) in April 1994. Became Section Chief of Electricity Standards Section 1, Electricity and Magnetism Division, National Metrology Institute of Japan (NMIJ) in October 2005; Division Head of Electricity and Magnetism Division, NMIJ in April 2007; and Principal Researcher of NMIJ in April 2009. Engages in R&D and standard provision of various electrical standards including the capacitance standard. Senior Principal Planning Officer of Planning Headquaters in October 2010. Received the Ichimura Prize in Technology (for Contribution) in 2002. In this paper, was in charge of the development of the capacitance standard based on quantized Hall resistance, the development of the remote calibration method for LCR standard, and planning and organization of the overall concept.

Atsushi Domae

Graduated from the Department of Electric and Electronic Engineering, Toyohashi Institute of Technology in March 2000. Joined the Electrotechnical Laboratory, Agency of Industrial Science and Technology (current AIST) in April 2000. Became the researcher of Electricity and Magnetism Division, NMIJ in April 2001, and person-in-charge of capacitance and AC resistance calibration in May 2006. Engages in R&D and standard dissemination of the capacitance and AC resistance standards. In this paper, was in charge of the development of the medium capacitance expansion system.

Discussions with Reviewers

1 Overall assessment

Comment (Katsuhisa Kudo, Safety and Environmental Protection Division, AIST)

You clearly defined the R&D goal in response to the demand of industry, and the scenario for standard dissemination all the way to the industrial site is very clear. The R&D was conducted according to a clear research road map based on the research potential that you accumulated over the years, while understanding the developments conducted at the NMIs around the world. Then, you established a highly original, world's top-level capacitance standard. You also developed an effective standard dissemination method to disseminate the primary measurement standard to the industrial sites, and contributed in establishing the traceability system for the capacitance standard that is one of the best in the world.

Comment (Akira Ono, AIST)

The development of the national standards for capacitance and the dissemination of these standards to the industrial sites are described in a birds-eye view along with the scenario. This is an excellent paper of the *Type 2 Basic Research* and *Product Realization Research*. It is not just the development of the national standards with the highest precision; the idea and the realization of the remote calibration to disseminate the standards to the industrial sites efficiently and rationally are also excellent outcomes of this research.

2 In reference to overall electrical standard

Comment (Katsuhisa Kudo)

The content of this paper is limited to capacitance standard. I got the impression that you are stating that the capacitance standard is particularly important in supporting the international competition of the manufacturing industries. In general, I think it is positioned as one of the core electrical standards, but does it have higher demand from industry compared to the voltage, current, or resistance standards? I think you should briefly refer to this in the "Introduction" to help the readers' understanding.

Answer (Yasuhiro Nakamura)

This paper focuses on the capacitance standard on which the authors have been mainly working to describe the scenario and the result of the R&D. As you indicated, capacitance is one of the core electrical standards, but other electrical standards such as the ones for voltage and resistance are also vital for supporting the international competition of the manufacturing industries. However, I thought the content may become unfocused if I talked about voltage and resistance standards, so in this paper, I intentionally emphasized the capacitance standard. As you indicated, I should discuss other electrical quantities in the "Introduction", and I added and revised the text accordingly.

3 Number of current calibration labs

Question (Katsuhisa Kudo)

In "2.2 Scenario for the dissemination of standard to industrial sites", the hierarchical structure of the calibration labs is shown in Fig. 1. You later mention three JCSS calibration labs, but it is unclear how many layers of Japanese calibration labs there are, or the number of calibration labs in each layer. Can you add some more figures in your explanations?

Answer (Yasuhiro Nakamura)

For the electrical standard, about 50 labs are accredited as the JCSS calibration labs. There are nine uppermost calibration labs (three labs for capacitance only) as shown in Fig. 1, and others are second-tier labs or below. I added the numbers of calibration labs to the text.

4 Situation at the NMIs of other countries

Question (Katsuhisa Kudo)

In "3.2 Development of the new method to respond to the demands", you describe the method for deriving the capacitance from the quantized Hall resistance, and this is something to be proud of. Please add the percentage of the NMIs that derive the standard from cross capacitance and those that do from quantized Hall resistance, as well as any foreign NMIs that employ the method newly developed by AIST.

Answer (Yasuhiro Nakamura)

Among the NMIs that use cross capacitors, the ones that realize high-precision capacitance are NMIA (Australia), NIST (USA), PTB (Germany), and LNE (France), as described in the text. Other than these, NIM (China) and VNIIM (Russia) realize the standard using the cross capacitor. The ones that derive their capacitance from the quantized Hall resistance, other than AIST, include NPL (England), CMS (Taiwan), and BIPM. However in all cases, the capacitance standard is realized using the conventional quadrature bridge circuit, and the multi-frequency system of AIST is a step ahead internationally.

5 New method of standard provision

Question (Katsuhisa Kudo)

It is written in "5 Future issues" that you are "considering the development of a new dissemination method…". While this may be a common issue for the metrological standards, do you have any ideas you can add?

Answer (Yasuhiro Nakamura)

Other than the "remote calibration method" described in this paper, another consideration is a system where a "long-term stable standard" is installed at the industrial sites, and this will enable calibration of the devices easily and at any time on site. For example, it may be possible to realize a "long-term highly stable standard voltage-current generation device" by combining the Josephson voltage standard and the thin-film thermal converter AC/DC standard. By developing such "technology that allows direct calibration at industrial sites" and then transferring this technology to industry, it may be possible to reduce the cost and time required for calibration. I think this will allow further rationalization of the traceability system.