Laboratory Report
of
National Metrology Institute of Japan (NMIJ/AIST)
and Japan Electric Meters Inspection Corporation (JEMIC)
2015-2017

At NMIJ/AIST, there are five research groups in the electrical standards area. They are the Applied Electrical Standards Group, the Quantum Electrical Standards Group, the Radio-Frequency Standards Group, the Electromagnetic Fields Standards Group, and the Electromagnetic Measurement Group.

The Applied Electrical Standards Group takes charge of the AC/DC transfer, the impedance and the power standards. The Quantum Electrical Standards Group covers the Josephson voltage, the quantized Hall resistance.

The Radio-Frequency Group takes charge of RF power, voltage, noise, and attenuation standards. The Electromagnetic Fields Group covers antenna properties, electric field and magnetic field standards. The Electromagnetic Measurement Group takes charge of RF impedance (S-parameter) standards and material properties.

Short summaries for research topics are as follows with recent references.

1. Josephson Voltage

We have developed an integrated quantum voltage noise source (IQVNS) that is fully implemented with superconducting circuit technology for Johnson noise thermometry (JNT). For precise measurements of Boltzmann's constant, the IQVNS chip was designed to produce intrinsically calculable pseudo-white noise to calibrate JNT systems. On-chip real-time generation of pseudo random codes with simple circuits achieved pseudo voltage noise with a harmonic tone interval less than 1 Hz, which was one order of magnitude finer than those of conventional quantum voltage noise sources. An experimental value of Boltzmann's constant obtained by JNT measurements has relative difference of a few part in 10^{-6} from the CODATA value.

A liquid-helium-free PJVS has been utilized since 2015 for calibrations of Zener voltage standards with the CMC values, 8.0 nV for 1 V and 45 nV for 10 V, same as those for our conventional JVS system cooled with liquid helium. The first direct comparison between our cryocooler-based PJVS system and the BIPM's new transportable PJVS system that is cooled with liquid helium has been carried out at NMIJ. The agreement within 5×10^{-12} at the output DC level of 10 V was confirmed between both the systems. We are now attempting to develop an AC voltage calibration system using PJVS. Development of Zener voltage standards are also now in progress in collaboration with ADC Corporation.

Fig.1 Prototype of a Zener votage standard.

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2. Resistance

Development of compact and ultra-stable 1 Ω, 10 Ω, 100 Ω and 1 kΩ standard resistors has been finished, and 10 kΩ resistors are in progress of evaluation and development. In 2016, we have finalized ~4 years of evaluation of 1 Ω and 10 Ω resistors, and the drift rates of those range of resistors are around 0.05 ppm/year and the temperature coefficients are around less than 0.1 ppm/˚C. Vibration test has been also carried out for 100 Ω resistors and showed no effect by the harsh (frequency: 16.7 Hz, amplitude: 4 mm in 3 axes) condition. It is demonstrated that this excellent performance is suitable for utilization in national metrology institutes and international comparisons.

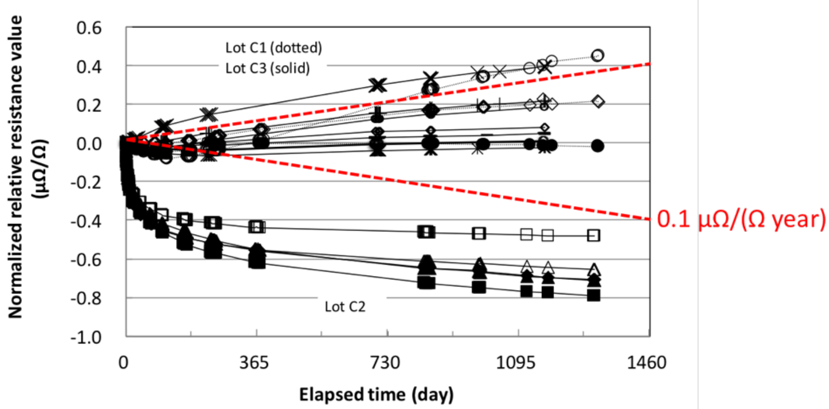

Fig. 2 Resistance histories (drifts) of 1Ω resistors.

Conventional single Hall bar QHR devices have been fabricated and several devices have been provided for several NMIs.

Newly designed 1 MΩ quantum Hall array resistance standard devices also have been fabricated. This device consists of 88 Hall bars on 8 × 8 mm^2 GaAs/AlGaAs chip ~~size~~ and its nominal value has only -0.0342 ppm difference based on $R_{K\text{-}90}$ from the integer value of 10^6. We observed a clear 1 MΩ plateau, and the measured value agreed with its nominal value within 0.3 ppm.

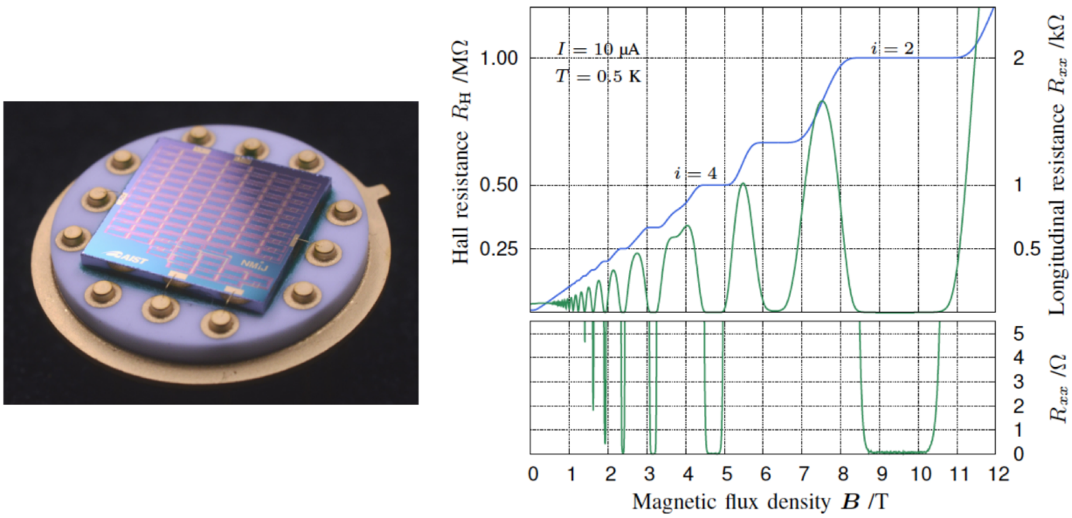

Fig. 3 Picture and Hall and longitudinal resistance curve of 1 MΩ array device.

To establish a relationship between the physical structure of electrical contact boundary and contact resistance, NMIJ developed a method for evaluating that using a physical simulated sample created via nanofabrication. Several samples with various diameter of "contact area" were made and their resistances were measured precisely. After removing influence of thickness of electrodes, it was demonstrated experimentally that our result is in good agreement with an expression for constriction resistance.

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3. DC Current (single electron pumping)

Towards a realization of the current standard based on the single-electron pumping, we investigate the physics of low-temperature electron transport phenomena in various types of single-electron devices, i.e. superconductor-insulator-normal-insulator-superconductor (SINIS) turnstiles, gate-confined quantum dots, and graphene- or nanotube-based single-electron transistors.

On SINIS turnstiles, in our early studies, we had discovered the new phenomenon that is a reduction of the single-electron pumping error induced by a weak magnetic field applied to the device. However, the origin of this phenomenon had remained poorly understood. To elucidate the underlying mechanism, we performed detailed measurement and analysis. First, in order to confirm the reproducibility of this phenomenon, we compare two SINIS devices of the identical structure each of which is fabricated with the aid of completely different nano-fabrication facilities and confirm the reproducibility as well as the universality. We then elucidate the mechanism based on a numerical simulation of the quasi-particle state in the lead electrodes.

Aiming at further reducing the pumping error, we extended the research to that based on another pumping mechanism. In one instance, we investigated a GaAs-based gate-defined quantum dot and demonstrated single-parameter pumping. In addition, we developed an air-bridge based parallel integration of this pump to demonstrate a synchronized parallel pumping that can generate a larger current otherwise unattained. In this study, molecular beam epitaxy growth of high-quality and gate-stable GaAs hetero-structure wafer is critical for the further development of the pumping accuracy. So, the improvement of the wafer quality is our future plan.

In addition to the single electron pumping, we start the experiment of the error counting using RF-reflectometry. The ac signal around a few hundred MHz signal is applied to the matching circuits in the dilution refrigerator. Using homodyne detection, we can succeed to detect the few tens MHz of impedance change of the device. Also we fabricated the capacitive coupled single electron device, namely single electron pumping device and single electron counter. Now we have plan auto correction system using arbitrary wave generator, FPGA and charge detector. This will make the improvement of the pumping accuracy and give us the intuitive information of the origin of charge pump errors. Alongside of these experiments, we also developed a new dilution refrigerator setup for measuring tiny ac current by employing low-noise superconducting-quantum-interference-device-based current amplifier as the first-stage amplifier. The measured current noise floor of this setup was at least one order of magnitude improved than that obtained with the setup that employs a semiconductor-based cryogenic current amplifier at the first-stage. We plan to take advantage of this setup to investigate various kinds of phenomena including non-equilibrium electron transport in mesoscopic devices and micro electromechanical systems.

These single-electron devices are planned to be integrated with the quantum metrology triangle experiment that combine the single-electron device with the quantum Hall resistance and Josephson voltage standards. Towards this futuristic experiment, we had introduced a dry dilution refrigerator; the large sample open space offered by this refrigerator allows us to integrate the whole components required for the triangle experiment including a cryogenic current comparator into one system. Electric noise filters and high-frequency wiring are now designed and constructed to complete this setup.

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4. LF-Impedance

We have been studying for measuring electric characteristics of lithium-ion batteries (LIBs) and super-capacitors by using an impedance spectroscopy method. Aim of this work is to establish the precision testing technique of charge-discharge cycle dependence of the characteristics which can provide an effective tool to examine the lifetime prediction of the energy-storage devices. Cycle dependence of impedance were measured for cylindrical 18650-type LIBs by our electrochemical impedance measurement system. We obtained the relation of charge-discharge cycle vs internal resistance components which were estimated based on the results of the impedance and on the equivalent circuit models. We are now engaging the improvement of the measurement system including measurement fixtures which are suitable for lamination-type batteries.

NMIJ has started a calibration service for rechargeable battery's impedance meters. Calibration range, 1 Ω - 100 Ω at 1 kHz, is a crucial for monitoring the long-term performance behavior of the batteries under test. Expanded uncertainties were estimated to be 0.13 mΩ/Ω in the range from 1 Ω to 10 Ω and to be 25 μΩ/Ω in the range from 10 Ω to 100 Ω ($k = 2$).

Fig. 4 Electrochemical impedance measurement system and fixture for measuring 18650-type batteries.

AC resistor calibration service has been kept in the range of 10 Ω up to 100 kΩ at 1 kHz and 10 kHz. Standard capacitor (dry-nitrogen or used silica dielectric) calibration service has been kept in the range of 10 pF up to 1000 pF at 1 kHz, 1.592 kHz.

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5. AC/DC transfer

NMIJ has provided ac-dc voltage difference transfer calibration of thermal converters in the voltage range from 10 mV to 1000 V and in the frequency range from 10 Hz to 1 MHz. We have been participating in APMP Comparison for " APMP.EM-K12" of AC/DC current transfer difference.

We have developed disc resistors for RVDs and μpots to re-establish the low-voltage ac–dc transfer standards at the NMIJ.

Toward a low-frequency AC voltage standard down to 10 Hz, we have extended the voltage range from 3 V to 10 V root-mean squared amplitude in AC-DC difference measurements of a thermal-voltage converter using our AC-Programmable Josephson voltage standard system. The overall uncertainty was evaluated as 1.1 μV/V (k = 2) for the frequency of 62.5 Hz. The measurement uncertainty showed a significant improvement compared to the conventional method based on a theoretical approach in the frequency range below 100 Hz.

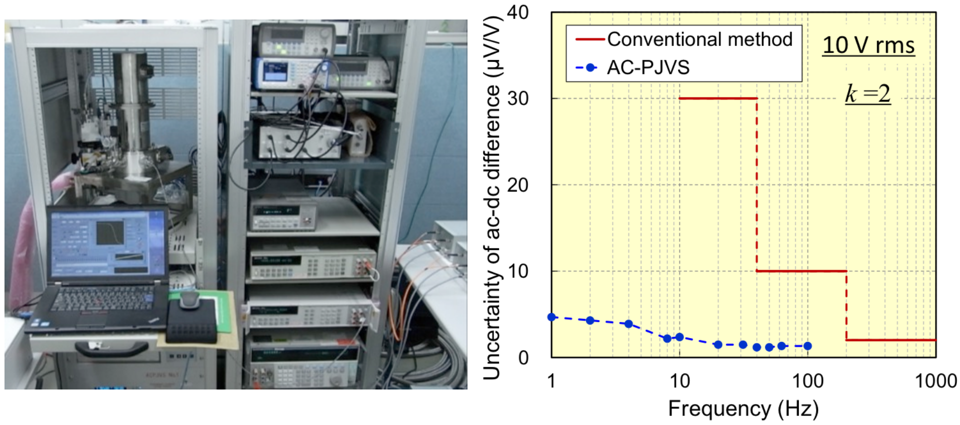

Fig. 5

With regard to a regular calibration service, we have provided a calibration service of AC voltmeters using a thermal converter in the frequency range from 4 Hz to 10Hz, 40 Hz to 100 kHz at the RMS voltage of 10 V, and 1 V.

Toward a waste-heat recovery, we have launched a new project toward Seebeck coefficient metrology that is the most fundamental physical property in the research field of thermoelectric energy conversion. To fulfill our purpose, we have developed a new method to determine absolute Seebeck coefficient using a Thomson-coefficient integration technique, and a superconductor thermocouple technique. So far, we have measured the absolute Seebeck coefficient of Pt using a superconductor thermocouple technique, because the thermoelectric power in the Meissner state is sufficiently small. In our experiment, by employing a $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ superconductor, the absolute Seebeck coefficients of the Pt sample have been determined in the temperature range up to 100 K.

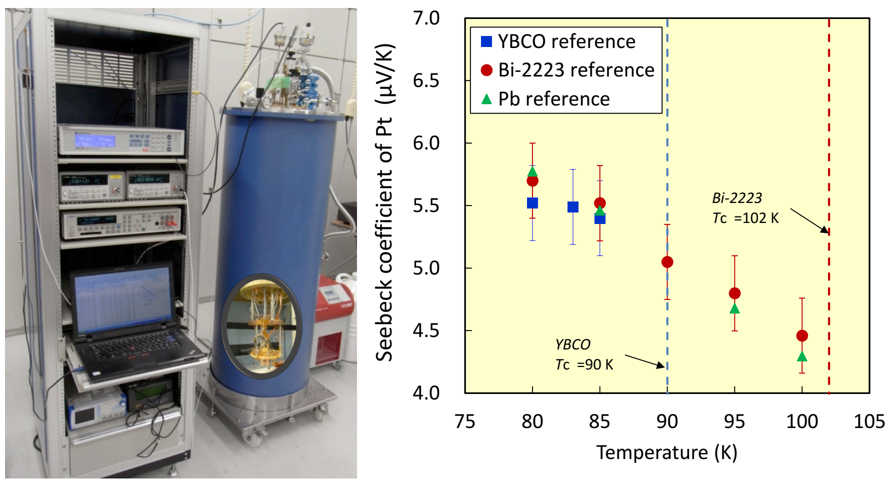

Fig. 6

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6. Power (NMIJ)

6.1. Power at NMIJ (harmonics, etc)

The NMIJ AC current ratio calibration system is renewed to extend the current range up to 100 amperes (current ratio up to 1000/1) in the frequency range between 45 Hz and 1 kHz. Over 1 kHz, the maximum input current is 50 amperes up to 4 kHz. Temperature influence due to the increase of input current has been investigated and the uncertainty of the entire calibration system is updated.The detail will be prepared as a conference paper.

A new evaluation method for wideband voltage dividers has been proposed and presented at the CPEM 2016.The method is based on introduction of two phase-locked reference voltage generators to a voltage divider evaluation system for their input and reference output. The system constructed allows wide voltage ratio and wideband evaluation for voltage dividers up to 1 MHz. The wide voltage ratio also includes decimal ratios (such as 1.01 V/100 V).

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6.2. Power at JEMIC (mains)

JEMIC has provided the primary active/reactive power/energy standards for the power frequencies in the voltage range from 50 V to 120 V and in the current range from 2.5 A to 50 A.

The standard individually measures voltage U and current I with two precise voltmeters and a shunt resistor, and phase θ with a precise digital phase meter. After these measurements, the active and reactive powers are calculated by $UI\cos\theta$ and $UI\sin\theta$, respectively. The representative expanded uncertainties under conditions of 100 V and 5 A are 22 μW/VA (power factor 1) and 10 μW/VA (power factor 0). In 2016, we calibrated 10 power meters and 70 energy meters.

JEMIC has been participating in APMP Key Comparison for "APMP.EM-K5.1" of AC power and energy.

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7. RF-power

The calibration system for WR-15 power meter was renewed. A frequency multiplier was substituted for a conventional backward-wave oscillator (BWO).

NMIJ are developing a new calorimeter for a higher frequency range up to 330 GHz.

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8. RF-Attenuation

NMIJ has successfully established a RF attenuation standard system in the frequency range of 33 GHz to 50 GHz (Q-band), and started the jcss calibration service from June 2015. The system is built by using the simple intermediate frequency (IF) receiver technique using a resistive step attenuators operated at 30 MHz, as an IF attenuation reference standard and a general-purpose receiver, as a level detector. By increasing the IF to 30 MHz, the noise effects caused by higher RF signals, such as the Q-band, can be kept small. This condition also allows us to use a general-purpose receiver as a sensitive level detector that facilitates the automation and long-term maintaining to the system. Traceability of the system then is ensured by performing periodic calibration to the IF attenuator reference standard at 30 MHz using the NMIJ attenuation standard system based on the voltage ratio of the IVD at 1 kHz.

Establishment of an attenuation reference primary standard in the frequency range of 110 GHz to 170 GHz has been also started. A millimeter wave VNA system, which consists of an intermediate frequency VNA and a set of millimeter wave S-parameter test extenders, is used as a measurement system. The traceability is ensured by the calibration to the intermediate frequency ports of the VNA using the calibrated step attenuator at 10.3 MHz.

NMIJ took an initiative to organize a CIPM Key Comparison of attenuation at 18 GHz, 26.5 GHz and 40 GHz using a step attenuator. This comparison has been registered in the KCDB under the identifier CCEM.RF-K26, with 15 laboratories (countries) declared to participate. Measurements of the first round loop can be said successful, although there were some delays in the delivery of the traveling standards between the participants. Currently, is in the second round loop and expected to be completed around June 2017.

A bilateral comparison of millimeter-wave attenuation in V band (50 GHz to 75 GHz) was performed between NMIJ and NMC. The final report was published in Measurement 82 (2016). Good agreement of the measurement results between both laboratories was verified in the attenuation range up to 60 dB.

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9. RF-Impedance

The terahertz waveguide flange, NMIJ developed, was standardized in the IEC 60154-2 standard. It was provides precise connection and connection reproducibility.

NMIJ is researching the material characterization at millimeter-wave frequency, precision on-wafer measurement techniques, printed electronics at millimeter-wave and non-linear load/source-pull measurement for GaN active devices. Furthermore, electromagnetic sensing techniques is also researching for the agriculture products and food.

Furthermore, NMIJ as a pilot laboratory is managing the CCEM key comparison (CCEM.RF-K5c.CL: S-parameter for PC3.5 in the range from 50 MHz to 33 GHz), the APMP supplemental comparison (APMP.EM.RF-S5.CL: Dimensionally-derived characteristic impedance for PC7, PC2.4 and PC1.85) and will start the pilot study for material characterization.

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10. Antennas, electric field, and magnetic field

A calibration service for the free-space antenna factor on loop antenna has been kept in the frequency range of 20 Hz to 30 MHz. The Draft A report of APMP supplementary comparison APMP.RF-S21.F is made circular among KRISS, NMIA and NMIJ since February 2017.
AC Magnetic field sensor calibration service has been kept in the range of 1 uT up to 150 uT at 50 Hz and 60 Hz.
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Calibration of the dipole antenna factor above a ground plane from 30 MHz to 1 GHz with the specific conditions (with horizontal polarization and at 2.0 m from the ground surface) is available. The free space dipole antenna factor in an anechoic chamber from 1 GHz to 2 GHz is also available.
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The free space antenna factor calibration service for broadband antenna for Biconical antenna (30 MHz to 300 MHz) and Log periodic dipole array antenna (300 MHz to 1000 MHz) are being performed using our original three antenna calibration method. Super broadband antenna (30 MHz to 1000 MHz) calibration service has been started from June 2015.
Calibration services for the gains of standard horn antennas are being performed from 1.7 GHz to 2.6 GHz and 18 GHz to 26.5 GHz using a extrapolation method. An antenna gain calibration service for ridged guide broadband horn antenna (1 GHz to 6 GHz) is available.

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An antenna gain calibration service for millimeter-wave standard gain horn antenna are being performed form 50 GHz to 75 GHz and 75 GHz to 110 GHz using a time-domain processing and extrapolation technique.

The calibration system of monostatic Radar Cross Section (RCS) for a trihedral corner reflector in W-band has been developed. The RCS calibration range is 3 dBsm to 12 dBsm at 75 GHz and 6 dBsm to 15 dBsm at 110 GHz. This RCS range corresponds to the reflector size L ranging from 75 mm to 125 mm. The expanded uncertainty of RCS was estimated to between 0.90 dB and 1.32 dB. This RCS calibration service has been started from June 2015.

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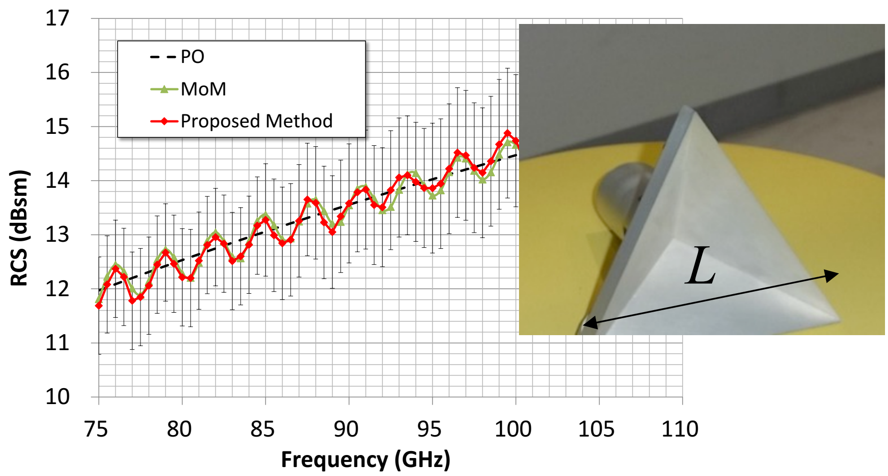

Fig. 7 RCS calibration results in W-band and an example of a trihedral corner reflector

The E-field transfer probe calibration from 20 MHz to 2 GHz in a G-TEM cell is available. The correction factor of a probe under calibration is provided when the probe output is 10 V/m. A TEM cell is employed as the standard E-field generator at low frequencies and the free space dipole antenna factor is used for the standard field generation in the anechoic chamber above 900 MHz. An optical E-field probe is employed to transfer the standard E-field strength into the G-TEM cell.

Contact: Takehiro Morioka, t-morioka@aist.go.jp.

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Digest.

11. Application of optical technology

We have developed a planar and a cylindrical scanner system for near- field antenna measurement using photonic sensor that is a few of grams in weight and a few of millimeters long. The systems are available about below 10 GHz.

We have developed an antenna radiation planar measurement system using photonic technologies. The systems are available about below 120 GHz.

We have developed a radio over fiber (RoF) transceiver usable attached to a RF network analyzer by microwave photonic technologies. It has a function of optical signal transmission and two-way conversion of E-O and O-E. Because the RoF transceiver is available being directly connected to antenna terminals and fed by only optical fibers, it does not affect the antenna characteristics and will become an ideal tool for antenna measurements.

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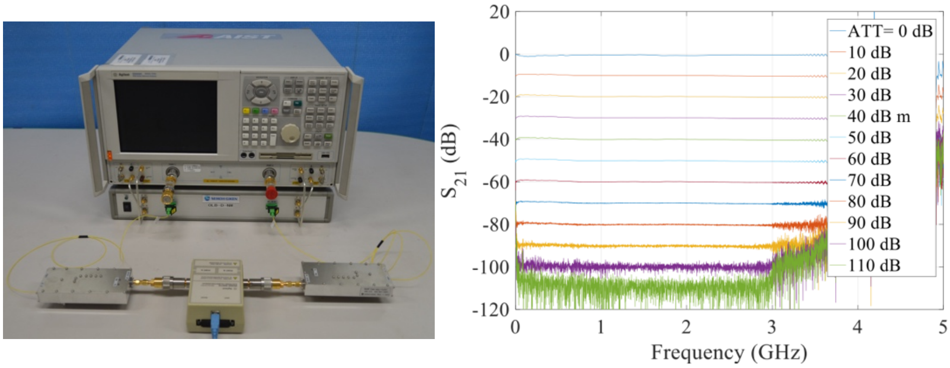

Fig. 8 Bi-directional RoF transceiver attached to a Vector network analyzer

12. Terahertz Metrology

NMIJ has been studying a terahertz calorimeter for measuring absolute power of a terahertz beam. We have succeeded in calorimetric measurement of the absolute power at 1 THz at sub-microwatt levels. The expanded uncertainty was estimated as 2.4% at 0.59 μW. The minimum measurable power level was expanded up to 30 nW.

NMIJ has demonstrated terahertz attenuator calibration using the calorimeter. We have shown measurement capability up to 12 dB with an expanded uncertainty of 0.19 - 0.84 dB ($k = 2$) at 1 THz.

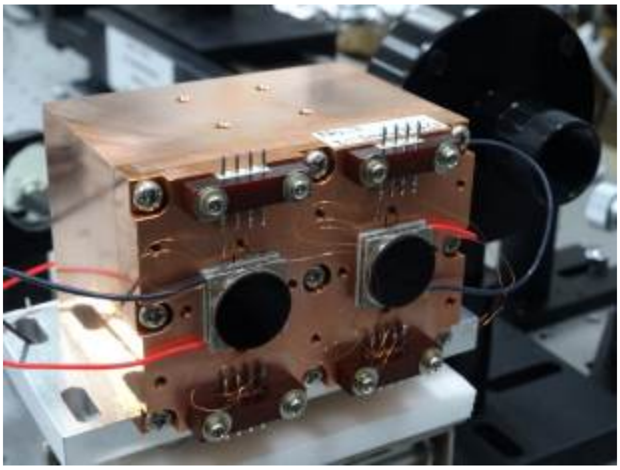

Fig. 9 Prototype of Twin type THz Caloriemeter

NMIJ has participated a comparison of transmittance using terahertz time-domain spectrometers among three institutes (NMIJ, NICT, RIKEN) to verify equivalence of measurements from different measurement systems. We have discussed to provide practice guidelines in transmittance measurement.

NMIJ is doing research on new terahertz detectors. We have demonstrated a terahertz pulse detection using a multilayer topological insulator.

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13. Material characterization

NMIJ is now researching and developing material characterization, i.e. dielectric permittivity measurements, at the microwave frequency. NMIJ has originally developed dielectric permittivity analysis with uncertainty optimization in the transmission/reflection measurement method for coaxial and waveguide lines. In the millimeter-wave frequency range, two types of free space measurement systems have been designed and installed. They are now being optimized and estimated the measurement uncertainty from 50 GHz to 330 GHz.

Furthermore, NMIJ as a pilot laboratory, switched from NIST, will start the Pilot study for dielectric permittivity measurement proposed by NIST as a former pilot laboratory in it. NMIJ is now considering and selecting the transfer material standards in the comparison. We are now proposing that two shapes of the transfer materials will be measured; plate samples by using the split-cylinder and/or split-post resonator methods, and block samples by using the waveguide method.

We have been studying for measuring electromagnetic characteristics of nano-carbon materials (CNT and Graphene, etc.) in collaboration with material groups in AIST. To promote the spread of developed measuring technologies, and to clarify the target of future research, we are now engaging and contributing the standardization activity relating the testing methods of nanomaterials (IEC TE113 WG8).

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