2-2-2 Power Meter Calibration 2 (1 mW, 75 Ω)

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NICT performs power meter calibration services in accordance with the Radio Law. Recently, a new power meter calibration system has been developed realizing a wide frequency range (from 100 kHz to 2 GHz) for 75-ohm (Type-N75) coaxial sensors with a typical power for calibration of 1 mW. In order to conduct accurate calibration, the simultaneous comparison method is adopted. The newly developed system has the expanded uncertainties (coverage factor k=2) of 2.5 % below 10 MHz and 1.2 % from 10 MHz to 2 GHz.

1 Foreword

For many years, NICT has carried out calibration service for power meters with 75 Ω input impedance Type-N coaxial connectors as input terminals. NICT has conducted this for 10W calibration power, and frequency range from 1 to 500 MHz. Recent years have brought progress in higher frequency band usage in systems using 75 Ω characteristic impedance transmission lines, such as 4K and 8K TV broadcasts. To meet increasing demand for power measurement, we developed a calibration system for low power meters with a 75 Ω input impedance Type-N coaxial connector input, compatible with 1 mW calibration power and wider bands (100 kHz to 2 GHz).

This paper describes the calibration method, advantages, calibration results, and calibration uncertainties of the calibration system developed.

2 Definitions of calibration factors

Generally, terminal type high frequency power meters are divided into a sensor part and indicator part, as shown in Figure 1, and these parts are connected by a dedicated cable. Calibration of a power meter seeks the calibration factor K, which is the ratio of the indicator value displayed on the power meter (P_M) vs. the power incident into the sensor part (P_{in}). The value of K is defined in the following equation.

$$K = \frac{P_M}{P_{in}} \tag{1}$$

For example, in the case where P_M is 0.99 mW and P_{in} is 1 mW, the calibration factor K is 0.99. If we know K, then P_M/K = 0.99/0.99 = 1 mW, so we can obtain the incident power from the indicator value and the calibration factor.

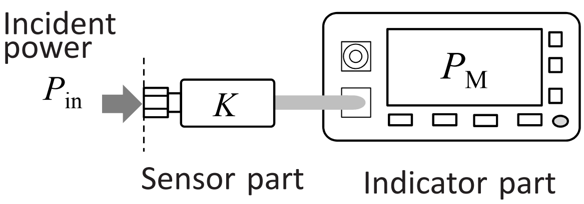

Fig. 1 Configuration of high frequency power meter

3 Calibration method

3.1 Calibration principles

Figure 2 shows the configuration of the comparison method, which is the simplest method for calibrating high frequency power meters. In this method, the same signal input from the signal source is measured by a standard power meter for which the calibration factor (K_{STD}) is already known. After the indicator value (P_M^{STD}) is obtained, the standard power meter is replaced with the power meter to be calibrated (“Device Under Test” (DUT)), for which the calibration factor (K_{DUT}) is unknown.) and measured. By obtaining the indicator value (P_M^{DUT}), we can then obtain the unknown K_{DUT} by Equation (2).

$$\text{Incident power} = \frac{P_M^{STD}}{K_{STD}} = \frac{P_M^{DUT}}{K_{DUT}} \qquad \therefore K_{DUT} = K_{STD}\frac{P_M^{DUT}}{P_M^{STD}} \tag{2}$$

Here, Equation (2) is for ideal conditions where the reference plane in Figure 2 has a reflection coefficient of 0. Actually, it is affected by the reflection coefficients of the power meter (Γ_{STD}, Γ_{DUT}) and the reflection coefficient of

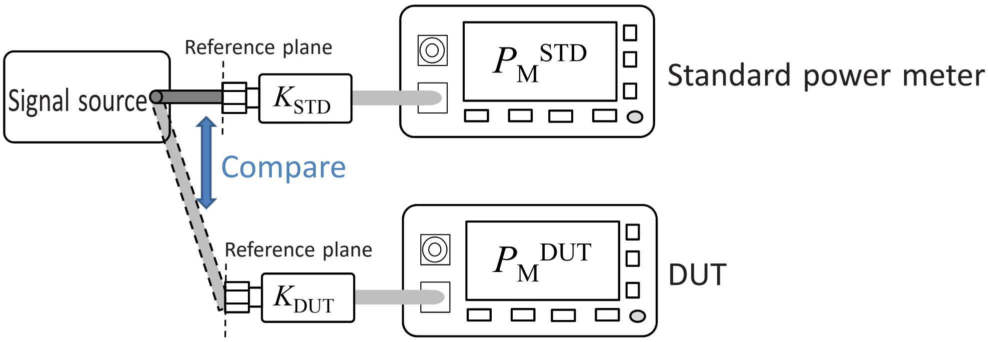

Fig. 2 Power meter calibration by comparison method

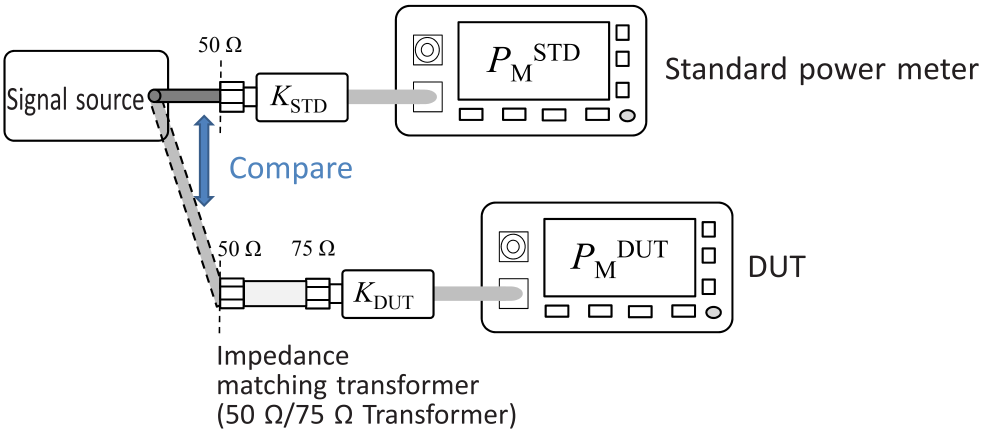

Fig. 3 Comparison method using an impedance matching transformer (50 Ω/75 Ω)

the signal source (Γ_G), so it becomes Equation (3).

$$K_{DUT} = K_{STD} \frac{P_M^{DUT}}{P_M^{STD}} \left| \frac{1-\Gamma_G \Gamma_{DUT}}{1-\Gamma_G \Gamma_{STD}} \right|^2 \tag{3}$$

In the comparison method, one must directly compare power meters that have coaxial connectors with the same characteristic impedance. However, Japan's national standard 1 mW high frequency power is only provided for 50 Ω coaxial lines, not provided using 75 Ω coaxial lines. Therefore, input impedance is also 50 Ω in the national standard traceable standard power meters that NICT has, so power meters that have connectors with 75 Ω input impedance cannot be calibrated.

To solve this problem, as shown in Figure 3, if we consider inserting a device that transforms characteristic impedance from 50 Ω to 75 Ω (hereinafter referred to as a "50 Ω/75 Ω Transformer") at the point before the DUT, then we must separately measure and correct for the electrical characteristics (*S* parameters) of the 50 Ω/75 Ω Transformer itself. And in the comparison method, Equation (3) also requires the signal source reflection coefficient (Γ_G), which is difficult to measure. In addition, the output of the signal source while measuring a standard power meter must be the same as while measuring the DUT. Therefore, the newly developed calibration system applies the simultaneous comparison method[1], in which output fluctuations of the signal source do not affect the calibration results, and measurement of the signal source reflection coefficient (Γ_G) is not necessary. Usually, even in the simultaneous comparison method, the standard power meter and DUT must have the same input impedance. But as shown in Figure 4, by combining a power splitter with a 50 Ω/75 Ω Transformer and fixed attenuator that corrects for that transformer's losses, one can calibrate a 75 Ω input impedance DUT by using a 50 Ω input impedance standard power meter.

In the system we developed, high frequency signal output from the signal source is input into the power splitter, and distributed. Part of the distributed output signal goes via the 50 Ω/75 Ω Transformer to the DUT. The other output signal goes via a fixed attenuator to the standard power meter.

3.2 Calibration steps

Calibration is done by a calibration program on a

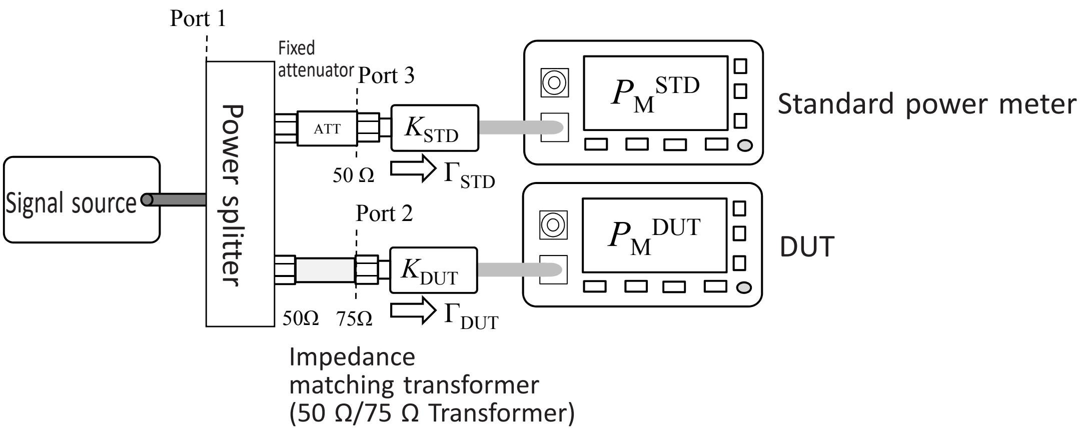

Fig. 4 Power meter calibration by simultaneous comparison method

Windows PC for control, in the following steps.

① The signal source is set to the calibration frequency, then it is output.

② Signal output is adjusted so the indicator value of the DUT is 1 mW.

③ The ratio of the indicator value of the DUT vs. the indicator value of the standard power meter is measured the set number of times (usually 100 times).

④ Steps ① to ③ are repeated for each calibration frequency.

⑤ Steps ① to ④ are repeated the set number of calibration times (usually 5 times).

⑥ From the measurement results, the equation below is used to obtain the calibration factor of the DUT $K_{DUT.}$

$$K_{DUT} = K_{STD}\left|\frac{S_{31}}{S_{21}}\right|^2\left(\frac{P_M^{DUT}}{P_M^{STD}}\right)M \tag{4}$$

Here, M is

$$M = \left|\frac{1-\Gamma_{g2}\Gamma_{DUT}}{1-\Gamma_{g3}\Gamma_{STD}}\right|^2 \tag{5}$$

Also,

$$\Gamma_{g2} = S_{22} - S_{32}\frac{S_{21}}{S_{31}} \tag{6}$$

$$\Gamma_{g3} = S_{33} - S_{23}\frac{S_{31}}{S_{21}} \tag{7}$$

The S parameters in Equations (4), (6) and (7) are the S parameters of the three port elements (hereinafter referred to as "Power Splitter") as the surfaces of Ports 1-3, which are the input/output surfaces of the power splitter, fixed attenuator, and 50 Ω/75 Ω Transformer in Figure 4. If we use a vector network analyzer to measure the S parameters of the device that has such input/output terminals with different impedance, then in through calibration before measurement, we connect a 50 Ω/75 Ω Transformer with unknown electrical characteristics and calibrate. The calibration method that removes the characteristics of this transformer is the "unknown through" calibration method[2]. After calibrating by this method, we measure the S parameters.

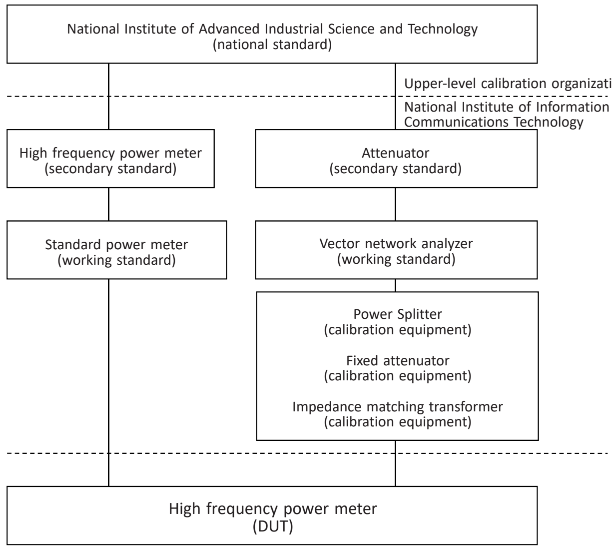

Fig. 5 Traceability system chart

3.3 Traceability to the national standard

Figure 5 shows the traceability system chart to the national standard, for this calibration. Standard power meters are calibrated by secondary standard high frequency power meters, using the calibration method shown in **2-2-1**. The vector network analyzer that measures the reflection coefficient and S parameters is calibrated by a secondary standard attenuator. These calibrations obtain traceability to the national standard.

4 Advantages

Figure 6 is a photo of the calibration system developed. The greatest advantage of this calibration system is that it can calibrate a 75 Ω DUT by using a standard power meter with 50 Ω input impedance. Other than this point, we describe points to consider when developing this system, calibration technology to obtain high quality calibration results, and maintenance items required to maintain performance.

(1) Considering workability and maintainability, as seen in Figure 6, all is stored in a small 19-inch (13 U) rack, including the DUT, to save space.

(2) For the connection plane (Ports 2 and 3 in Figure 4) between the standard power meter and DUT, in order to make uniform the effects on connection plane due to the power meter's sensor part's own weight, we arranged to vertically connect the sensor parts, as seen in Figure 6.

(3) To assess the variability due to connection of the connector of the sensor part of the DUT, after finishing calibration each time (performed 5 times), the sensor section is rotated roughly 72-degrees (360 degrees divided by five), then reconnected and measured. To prevent connector connection plane wear due to rotation, one should make sure to detach the connector before rotating and reconnecting it.

(4) When connecting the connectors, use a torque wrench and tighten to the specified torque, for reproducibility of measurements.

(5) The connection plane of the standard power meter (50 Ω) and DUT (75 Ω) are both Type-N coaxial connectors, as shown in Figure 7. Other than the diameter sizes of the center conductors (arrows point to them in Figure 7), they have the same dimensions, so it is very difficult to tell them apart. If someone mistakenly connects the standard power sensor (50 Ω male) to Port 2 (75 Ω female) of Figure 4, then the diameter of the center conductor will differ, which will damage the center conductor of Port 2 (75 Ω female). To prevent such mistakes, we write a warning note on the side of the connection to Port 2, so calibrator check again that the connector they want to connect is a "75 Ω Type-N connector."

(6) Maintenance Items

(a) To check normalcy of this calibration system, once each year, we calibrate a DUT to check validity, confirm that the system is working normally, and check changes of calibration results over the years and validity.

(b) To check traceability, once each half year, we use a vector network analyzer to measure the attenuation amount of a high frequency attenuator (secondary standard device), and compare vs. an upper-level calibration value, to check changes over the years and validity. We also use this vector network analyzer to measure the *S* parameters

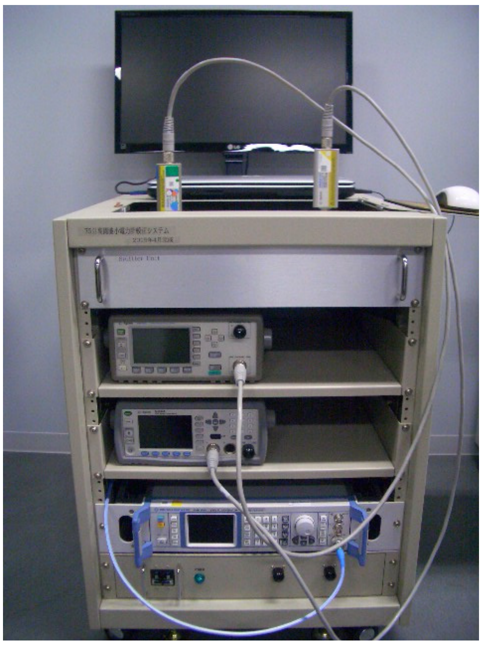

Fig. 6 High frequency power meter calibration system (1 mW, 75 Ω) photo

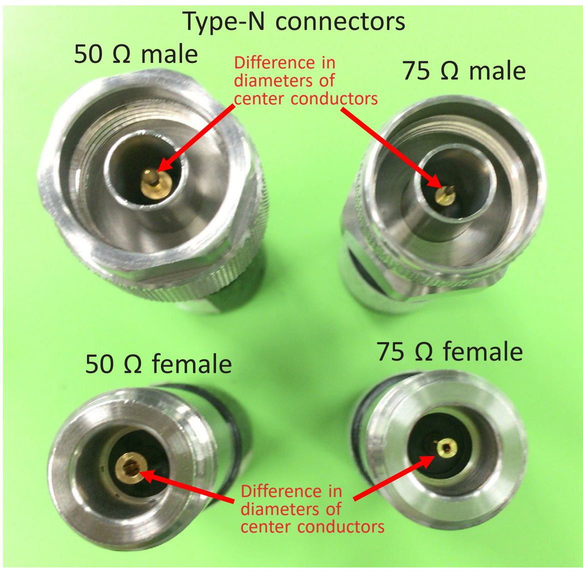

Fig. 7 Shapes of type-N coaxial connectors

of the Power Splitter, and check changes over the years and validity. Figure 8 shows an example of *S* parameters measurement results. The difference between S_{21} and S_{31} (about 0.2 dB) is the difference between attenuation amounts of a fixed attenuator vs. a 50 Ω/75 Ω Transformer. This difference is corrected by $|S_{31}/S_{21}|^2$ in Equation (4), so it does not affect calibration results.

5 Calibration results

We used the calibration system we developed to calibrate a 75 Ω input impedance sensor part (made by Keysight Technologies: 8483 A) and indicator part (also by Keysight: E4418 B) as the DUT.

Figure 9 shows an example of calibration results. The solid line (●) is calibration results by the calibration system now developed by NICT. The dashed line (▲) is the cali-

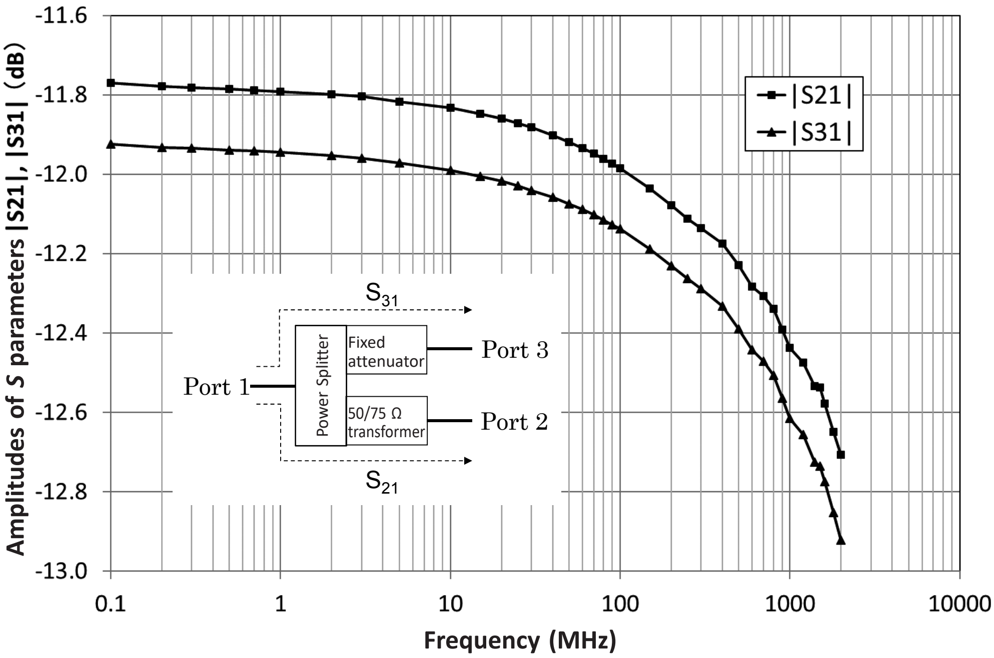

Fig. 8 Power splitter's S parameters measurement results example

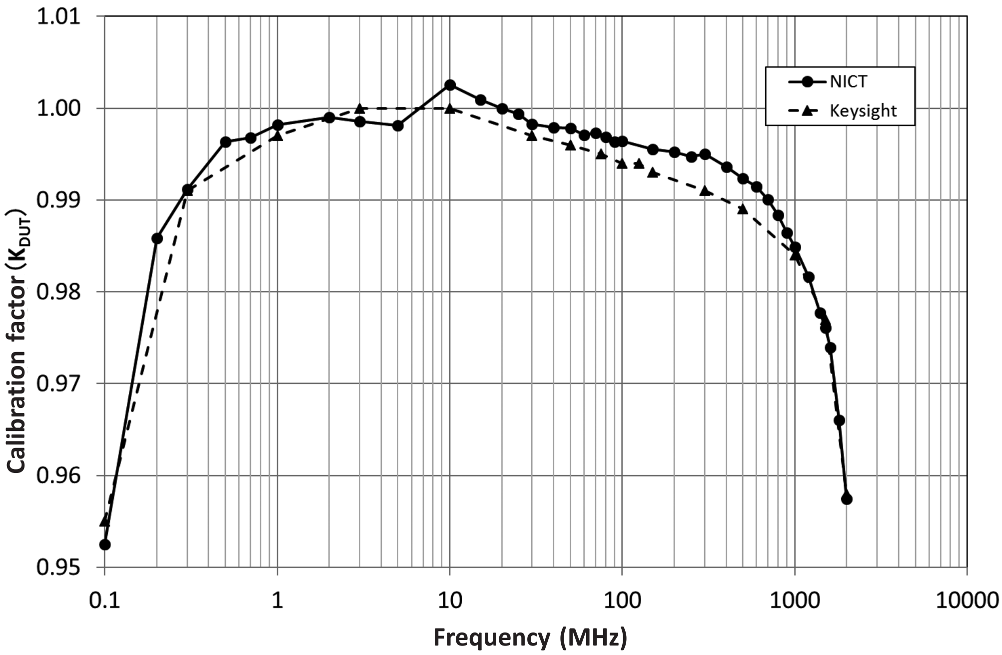

Fig. 9 Calibration results example

bration factors by Keysight Technologies; these calibration factors are traceable to the U.S. National Institute of Standards and Technology (NIST). In all frequencies, they match within the range of uncertainty described below, so the calibration results can be considered good.

6 Uncertainty of calibration

Uncertainty u (K_{DUT}) attached to calibration results by the calibration system developed is in the following equation, according to the law of propagation of uncertainty [3].

$$\frac{u(K_{\mathrm{DUT}})}{K_{\mathrm{DUT}}} = \sqrt{\begin{aligned}&(+1)^2\left\{\frac{u(K_{\mathrm{STD}})}{K_{\mathrm{STD}}}\right\}^2 + (+2)^2\left\{\frac{u(|S_{31}|)}{|S_{31}|}\right\}^2 + (-2)^2\left\{\frac{u(|S_{21}|)}{|S_{21}|}\right\}^2 \\ &+ (+1)^2\left\{\frac{u(P_{\mathrm{M}}^{\mathrm{DUT}})}{P_{\mathrm{M}}^{\mathrm{DUT}}}\right\}^2 + (-1)^2\left\{\frac{u(P_{\mathrm{M}}^{\mathrm{STD}})}{P_{\mathrm{M}}^{\mathrm{STD}}}\right\}^2 + (+1)^2\left\{\frac{u(M)}{M}\right\}^2 \\ &+ (+1)^2\left\{\frac{s(K_{\mathrm{DUT}})}{K_{\mathrm{DUT}}}\right\}^2\end{aligned}} \quad (8)$$

In Equation (8), looking at each source of uncertainty one by one, starting from the first item on the right side, they are: ① Calibration uncertainty of standard power meter, ② Uncertainty of attenuation amount between Power Splitter Ports 1–3 (S parameters), ③ Uncertainty of attenuation amount between Power Splitter Ports 1–2 (S parameters), ④ Measurement resolution of DUT, ⑤ Measurement resolution of standard power meter, ⑥ Mismatch between the standard power meter and Power Splitter, and between DUT and Power Splitter, ⑦ Variability of measurements. Here, the value in the parentheses directly before the brackets on the right expresses the sensitivity coefficient $c(x)$ for each factor in Equation (8).

① uses the uncertainty of upper-level calibration (normal distribution). ② and ③ use the uncertainty when measuring by a vector network analyzer calibrated by a mediation high frequency attenuator that is traceable to national standard (normal distribution). ④ and ⑤ are determined from the displayed digits of the standard power meter and DUT (uniform distribution). ⑥ is measured and calculated reflection coefficients of the standard power meter and DUT, and S parameters of the Power Splitter (U distribution). ⑦ is measurements repeated five times to obtain the variability (normal distribution).

Figure 10 shows uncertainty comparison results. Compared to the uncertainty of calibration by Keysight Technologies, uncertainty is larger at under 10 MHz, caused by the large uncertainty of upper-level calibration. At 10 MHz or higher, it is similar or 0.1 % less than the uncertainty of Keysight Technologies. Therefore, we judge the system has sufficient performance in calibration service.

Tables 1 and 2 show examples of calculations of calibration uncertainty. Table 1 is a calibration uncertainty budget at 100 kHz, where uncertainty is highest. Table 2 is the budget at 2 GHz, the highest frequency. Table 1 shows that

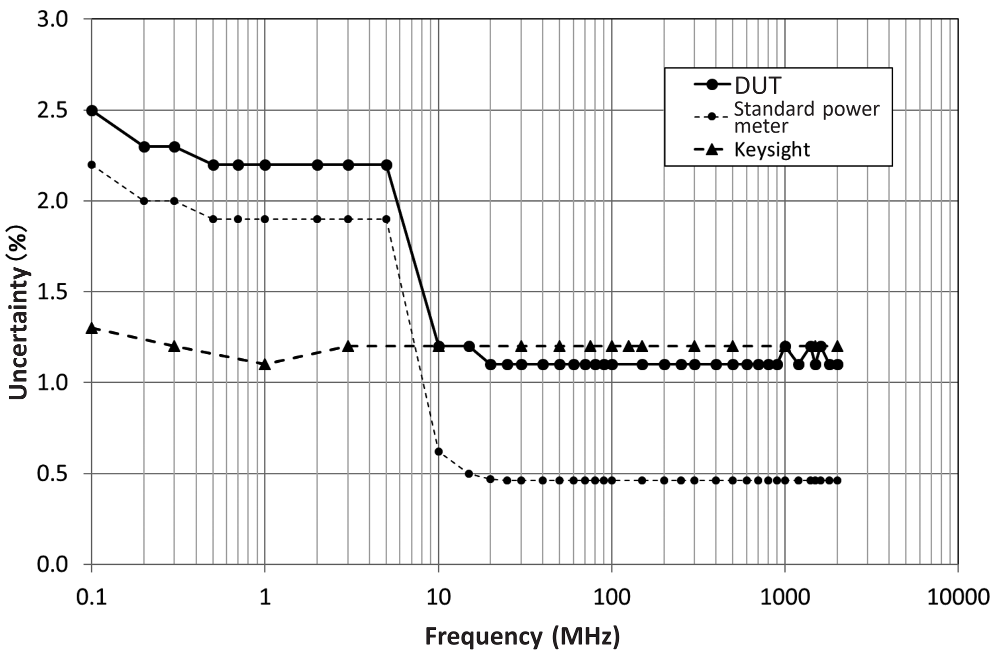

Fig. 10 Uncertainty comparison

Table 1 Uncertainty budget example (100 kHz, 1 mW)

Sources of uncertainty		Uncertainty	Distribution	Divisor	Standard uncertainty u(x)	Sensitivity coefficient c(x)	Contribution to uncertainty|c(x)|u(x)
K_{STD}	Standard	2.20 % (k=2)	Normal	2	1.10 %	1	1.10 %
S_{31}	Attenuation	0.015 dB	Normal	1	0.17 %	2	0.35 %
S_{21}		0.015 dB	Normal	1	0.17 %	-2	0.35 %
P_M^{DUT}	Power meter resolution 4 digits	0.05 %	Uniform	$\sqrt{3}$	0.03 %	1	0.03 %
P_M^{STD}		0.05 %	Uniform	$\sqrt{3}$	0.03 %	-1	0.03 %
M	Mismatch	0.06 %	U	$\sqrt{2}$	0.04 %	1	0.04 %
$s(K_{DUT})$	Repeatability	0.09 %	Normal	$\sqrt{5}$	0.04 %	1	0.04 %
Combined standard uncertainty							1.21 %
Extended uncertainty (k = 2)							2.5 %

Table 2 Uncertainty budget example (2 GHz, 1 mW)

Sources of uncertainty		Uncertainty	Distribution	Divisor	Standard uncertainty u(x)	Sensitivity coefficient c(x)	Contribution to uncertainty |c(x)|u(x)
K_{STD}	Standard	0.46 % (k=2)	Normal	2	0.23 %	1	0.23 %
S_{31}	Attenuation	0.015 dB	Normal	1	0.17 %	2	0.35 %
S_{21}		0.015 dB	Normal	1	0.17 %	-2	0.35 %
P_M^{DUT}	Power meter resolution 4 digits	0.05 %	Uniform	$\sqrt{3}$	0.03 %	1	0.03 %
P_M^{STD}		0.05 %	Uniform	$\sqrt{3}$	0.03 %	-1	0.03 %
M	Mismatch	0.07 %	U	$\sqrt{2}$	0.05 %	1	0.05 %
$s(K_{DUT})$	Repeatability	0.11 %	Normal	$\sqrt{5}$	0.05 %	1	0.05 %
Combined standard uncertainty							0.55 %
Extended uncertainty (k = 2)							1.1 %

calibration uncertainty u (K_{STD}) of the standard power meter is the main factor that increases uncertainty. This is the uncertainty attached to calibration results at an upper-level calibration organization (National Institute of Advanced Industrial Science and Technology), so it is difficult for us to improve that ourselves. Other than that, uncertainty of S parameters u ($|S_{31}|$)and u ($|S_{21}|$) are factors. We will investigate methods to reduce the uncertainty of these attenuation amount measurements in the future.

7 Conclusion

For the 100 kHz to 2 GHz frequency range, we developed a low power (1 mW) power meter calibration system for 75 Ω input impedance Type-N coaxial connectors. We did actual calibrations, and sought the system's calibration uncertainties.

We found that power meter calibration is possible with 2.5 % expanded uncertainty at less than 10 MHz, or 1.2 % at 10 MHz or higher.

An issue for the future is how to maintain and improve calibration quality, including investigation of methods to reduce uncertainty of S parameters of the Power Splitter.

Appendix. Derivation of Equation (4)

In the simultaneous comparison method calibration system shown in Fig. 4, if we use S parameters to express the status, with the signal source connected to Port #1, DUT to Port #2, and standard power meter to Port #3, we obtain the following equations.

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{23} & S_{33} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \tag{A.1}$$

$$a_1 = a_G + \Gamma_G b_1 \tag{A.2}$$

$$a_2 = \Gamma_{\mathrm{DUT}} b_2 \tag{A.3}$$

$$a_3 = \Gamma_{\mathrm{STD}} b_3 \tag{A.4}$$

Here, the S matrix expresses characteristics of the 3 port circuit shown in the dashed lines containing the Power Splitter. a_G is the source power from the signal source, Γ_G is the reflection coefficient of the signal source, Γ_{DUT} is the reflection coefficient of the DUT, and Γ_{STD} is the reflection coefficient of the standard power meter.

From these equations, we obtain below the power $P_{\mathrm{in}}^{\mathrm{DUT}}$ incident into the DUT and power $P_{\mathrm{in}}^{\mathrm{STD}}$ incident into the standard power system

$$P_{\mathrm{in}}^{\mathrm{DUT}} = |b_2|^2 = \left| \frac{D_{(2S1)(11)}}{D} \right|^2 |a_G|^2 \tag{A.5}$$

$$P_{\mathrm{in}}^{\mathrm{STD}} = |b_3|^2 = \left| \frac{D_{(3S1)(11)}}{D} \right|^2 |a_G|^2 \tag{A.6}$$

Where,

$$D = \det \begin{bmatrix} 1 - S_{11}\Gamma_G & -S_{12}\Gamma_{\mathrm{DUT}} & -S_{13}\Gamma_{\mathrm{STD}} \\ -S_{21}\Gamma_G & 1 - S_{22}\Gamma_{\mathrm{DUT}} & -S_{23}\Gamma_{\mathrm{STD}} \\ -S_{31}\Gamma_G & -S_{32}\Gamma_{\mathrm{DUT}} & 1 - S_{33}\Gamma_{\mathrm{STD}} \end{bmatrix} \tag{A.7}$$

$$D_{(2S1)(11)} = \det \begin{bmatrix} S_{21} & -S_{23}\Gamma_{\mathrm{STD}} \\ S_{31} & 1 - S_{33}\Gamma_{\mathrm{STD}} \end{bmatrix} = S_{21} \left\{ 1 - \left(S_{33} - S_{23} \frac{S_{31}}{S_{21}} \right) \Gamma_{\mathrm{STD}} \right\} \tag{A.8}$$

$$D_{(3S1)(11)} = \det \begin{bmatrix} 1 - S_{22}\Gamma_{\mathrm{DUT}} & S_{21} \\ -S_{32}\Gamma_{\mathrm{DUT}} & S_{31} \end{bmatrix} = S_{31} \left\{ 1 - \left(S_{22} - S_{32} \frac{S_{21}}{S_{31}} \right) \Gamma_{\mathrm{DUT}} \right\} \tag{A.9}$$

Here, det[A] expresses the matrix equation of matrix A.

Now, if we measure and compare two incident powers at the same time, from equations (A.5) and (A.6), we obtain

$$\frac{P_{\mathrm{M}}^{\mathrm{DUT}}}{P_{\mathrm{M}}^{\mathrm{STD}}} = \frac{K_{\mathrm{DUT}}}{K_{\mathrm{STD}}} \frac{P_{\mathrm{in}}^{\mathrm{DUT}}}{P_{\mathrm{in}}^{\mathrm{STD}}} = \frac{K_{\mathrm{DUT}}}{K_{\mathrm{STD}}} \left| \frac{D_{(2S1)(11)}}{D_{(3S1)(11)}} \right|^2 = \frac{K_{\mathrm{DUT}}}{K_{\mathrm{STD}}} \left| \frac{S_{21}}{S_{31}} \right|^2 \left| \frac{1 - \left(S_{33} - S_{23} \frac{S_{31}}{S_{21}} \right) \Gamma_{\mathrm{STD}}}{1 - \left(S_{22} - S_{32} \frac{S_{21}}{S_{31}} \right) \Gamma_{\mathrm{DUT}}} \right|^2 \tag{A.10}$$

Here, we used the relationship

$P_{\mathrm{in}}^{\mathrm{DUT}} = P_{\mathrm{M}}^{\mathrm{DUT}} / K_{\mathrm{DUT}}$ and $P_{\mathrm{in}}^{\mathrm{STD}} = P_{\mathrm{M}}^{\mathrm{STD}} / K_{\mathrm{STD}}$

If we transform the equation, we obtain Equation (4) as shown below.

$$K_{\mathrm{DUT}} = K_{\mathrm{STD}} \left| \frac{S_{31}}{S_{21}} \right|^2 \left(\frac{P_{\mathrm{M}}^{\mathrm{DUT}}}{P_{\mathrm{M}}^{\mathrm{STD}}} \right) \left| \frac{1 - \left(S_{22} - S_{32} \frac{S_{21}}{S_{31}} \right) \Gamma_{\mathrm{DUT}}}{1 - \left(S_{33} - S_{23} \frac{S_{31}}{S_{21}} \right) \Gamma_{\mathrm{STD}}} \right|^2 \tag{A.11}$$

In the equation's derivation process, matrix equation D shown in Equation (A.7) was eliminated, so there is no need to actually obtain it. This means that the signal source reflection coefficient (Γ_G) can be unknown, which is a great advantage of the simultaneous comparison method.

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