

## [ RESEARCH ]

# Broadband RF Power Standard for 7 mm Coaxial Waveguide in the Frequency Range of 10 MHz-18 GHz - Design and Fabrication -

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An automatic calibration system for a broadband RF power meter was developed in the frequency range from 10 MHz to 18 GHz for the APC 7 connector with a 7 mm coaxial waveguide. This system is composed of an isothermal control type dry calorimeter, a broad band stabilized signal source and a controller. The measurement are easily performed by a graphic programming method. RF power is measured directly by the calorimeter and the calibration factor is determined by connecting a device under test at the measuring port. The design, fabrication, basic characteristics and calibration experiments are described.

### §1 Introduction

With recent development of the radio frequency (RF) utilization technology, the necessity of precise broadband measurement technique has increased in microwave and millimeter wave area. Following these needs, various RF measuring instruments have been developed and come commercially available.

One of the basic quantity in the calibration of these instrument is RF power. At ETL, we have been engaged in development of RF power standard. As the microwave power standards (the specific standard of the measurement law) so far, those of the 14 mm coaxial waveguide for 1 and 3 GHz, and that of the X band rectangular waveguide for 10 GHz were established. They have been used for calibrations of the secondary standards of Japan Quality Assurance Organization (JQA) and Communications Research Laboratory (CRL) in each point frequency. JQA is doing calibrations to accredited laboratories and general users. We have also developed a standard at the frequency of 35 GHz<sup>1)</sup> and 94 GHz<sup>2)</sup> to the waveguide power but broadband RF power standards are remained as to be developed.

In the field of RF power standard, many countries in which the leaders of such as Europe, United State and also the advanced Asian countries have been developing broadband RF power standards, and are aggressively carrying forward to expansion of the range. On the other hand, the scheme of the Mutual Recognition of Arrangement (MRA) of the calibration results among the national standard laboratories has begun in last autumn. Various international comparisons are planed for kinds of measurables by the Consulting Committee of Electricity (CCE), Radio Frequency Working Group (GT-RF) of the International Metrology Committee (CIPM) and the Asian Pacific Metrology Program (APMP).

In many standard laboratories, a microcalorimeter method is often used to realize a RF power standard. The method makes a bolometer (thermistor mount or barretter mount) as a calorimetric load and measures its substitution characteristics(effective efficiency) using detection of temperature change of the mount<sup>3-6)</sup>. Using the mount of which effect efficiency is beforehand determined by the microcalorimeter, calibration factor of a device under test (DUT) can be obtained easily by a comparison measurement. The standard of ETL above-

mentioned is based on this method.

Besides, there is a way of measuring directly incident power and calibrating a DUT. As the part of new broadband power standard development, we did and reported so far researches of broadband power measurement for the 2.9 mm coaxial waveguide with K connector<sup>7)</sup>.

Here, aiming at a broadband calibration of RF power meter with a APC 7 connector of 7 mm coaxial waveguide, a power standard system has been newly developed using a broadband calorimeter in the frequency range from 10 MHz to 18 GHz. The system has been developed in the viewpoint especially of high accuracy. The overview of the design, the fabrication of the system, calibration experiments are described.

## §2 Broadband power meter calibration system

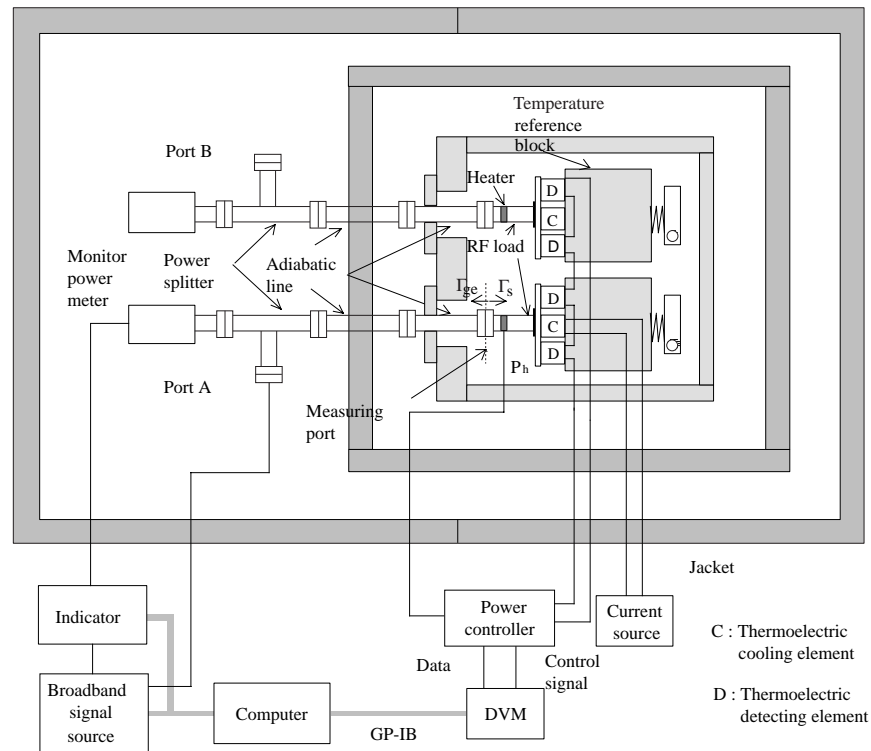
This system measures the calibration factor of the DUT at each frequency by direct measuring method of RF power described in the beginning. The calibration

factor is a ratio of measured RF power to the incident RF power into a DUT.

**Fig. 1** shows the block diagram of the developed system. Firstly, setting a signal source to the measurement frequency, RF power measurement is made for incident power at the measuring port. At the same time the system records the monitor power which is proportional to it. Then, changing the frequency of the signal source one after another, the system executes these measurements in all the frequencies. Thus, we obtain the power splitting ratio that is the RF power divided by the monitor power.

Next, outer three jackets, the temperature reference block and the RF load are removed, and then DUT is connected at the measuring port. Measurement of the DUT and the monitor power at each frequency are carried out and the calibration factor of the DUT is calculated.

The substitution coefficient and RF power measurement are made by connecting RF load and, the cooling/detection part to the measuring port as in the figure. The cooling/detection part comes in thermally contact



**Fig. 1** Automatic calibration system for a broadband power meter

with the rear surface of the RF load. The reason why the calibration of a DUT is done at the output port of the adiabatic line is to make the uncertainty due to the line loss as small as possible. The structure of the calorimeter is a twin-type calorimeter using an isothermal control method with thermoelectric elements. For the input line, two adiabatic lines of the same type are used in series and the calorimeter body is covered with triple jackets to improve the temperature stability.

The signal source is composed of a leveling loop using a power splitter and a monitor power meter to reduce a source mismatch<sup>8)</sup>. Splitting RF output of the synthesizer, one part is supplied to the RF load through the adiabatic line and the other part is supplied to the monitor power sensor. The output of indicator of the monitor power sensor is fed back to the level control terminal of the synthesizer. This leveling loop reduces the source mismatch. The monitor power is measured by a digital voltmeter (DVM) and the data is read by the computer through GP-IB. The broadband RF synthesizer is also connected with the computer through GP-IB. The computer programs of the control and measurement are developed using a graphic programming. The principle and the procedure of measurement is as follows.

At first, constant cooling current is applied to the thermoelectric cooling element and the temperature difference is fed back to the built-in heater through the power controller. The amount of the cooling current is pre-determined so that the bias power comes to 1.2~2 times of RF power level. The temperature of the RF load is controlled so to equal the temperature of the thermal reference block. Under this isothermal control, RF power is determined as the change of bias power of the heater while it is turned off and on. Simultaneously, the monitor power is measured. Then, the power splitting ratio of the RF power and monitor power is calculated at each frequency. For a calibration of a DUT, the RF load is exchanged to the DUT, and both DUT and monitor power meter are measured at all the frequencies. When the DUT connector type is different from APC 7

(such as N type), an adapter becomes necessary. Also, an extension line with the suitable length is necessary when a DUT is too big to connect directly to the measuring port. Including these case, calibration factor  $K$  of the DUT is expressed as follows<sup>7)</sup>.

$$K = \frac{P_u}{C_d P_{ms} \eta_l \eta_a |1 - \Gamma_g \Gamma_u|^2} \quad (1)$$

Where,  $P_u$  is the measured power of DUT.  $C_d$  is the coupling ratio of measured RF power  $P_{rf}$  and the monitor power  $P_{ms}$ .  $P_{ms}$  is the measured monitor power.  $\Gamma_g$  is the reflection coefficient of the signal source and  $\Gamma_u$  is that of the DUT.  $\eta_a$  and  $\eta_l$  is the power transmission efficiency of the adapter and the extension line, respectively.

In Eq. (1),  $|1 - \Gamma_g \Gamma_u|^2$  will be evaluated separately as an uncertainty factor. In the case of no use of an adapter and an extension line, both  $\eta_a$  and  $\eta_l$  equals unity.

On the other hand,  $C_d$  is determined by the following equation<sup>7)</sup>.

$$C_d = \frac{P_{rf}}{P_{ms}} \quad (2)$$

$P_{rf}$  is obtained from the following equation by a calorimetric measurement.

$$P_{rf} = \frac{k}{1 - |\Gamma_s|^2} \left(1 - \frac{q\alpha}{1 - \alpha}\right) (P_{h1} - P_{h2}) \quad (3)$$

Where,  $P_{h1}$  and  $P_{h2}$  are the heater power for RF power turned off or on, respectively.  $k$  is the substitution coefficient of RF and DC. It is defined as the ratio of the DC power input to RF load and the calorimetric measured power. To compensate the incident DC current polarity,  $k$  should be determined as a mean value for the positive or negative DC current<sup>7)</sup>.  $|\Gamma_s|$  is the reflection coefficient of the RF load.  $q$  is the ratio of heat transferred to RF load to the heat generated by the loss of the adiabatic line.  $\alpha$  is the rate of the attenuation by the adiabatic line.

$q\alpha/(1-\alpha)$  means the rate of the excess heating of RF load due to the RF loss in the adiabatic line.

### §3 Components of the system

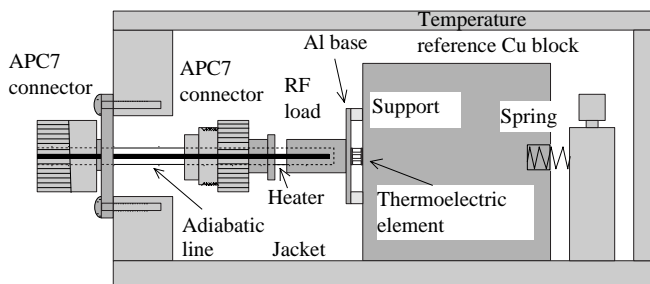
In the development of the broadband coaxial calorimeter, the following items are especially considered.

- ! An adiabatic line having excellent RF transmission characteristics
- " An RF load with low reflection and small thermal capacity
- # A low noise and highly sensitive temperature difference detector and a refrigerator
- \$ Temperature stabilization jackets

The cross sectional view of the calorimeter is shown in **Fig. 2** but this illustrates a part with only single port and single adiabatic line.

As for the adiabatic line, the outer conductor caliber is 7 mm, the outside diameter of inner conductor is 3.04 mm and the length of line is 37.9 mm. To make the heat resistance high, the outer conductor is made from stainless steel of 0.5 mm thickness and the inner conductor is made from ceramic to heighten thermal insulation. Both of the surface is plated with Gold to Nickel base plate. As for the both edges of the inner conductor, a spring type contact mechanism of the APC 7 connector is used. The measuring port has no coupling nut to decrease the thermal capacity. The RF characteristics of the adiabatic line are as follows.

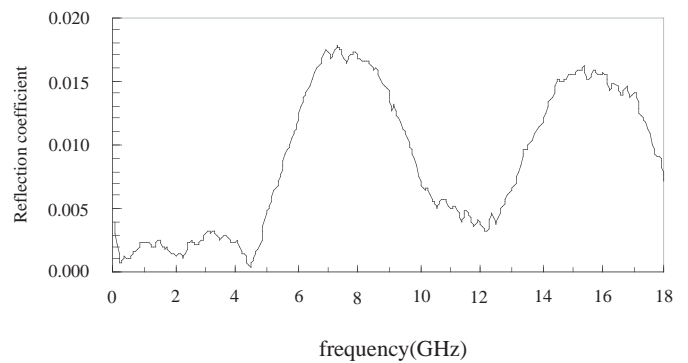
The reflection coefficient of the adiabatic line was measured using a network analyzer and is shown in **Fig. 3**. **Fig. 4** shows the RF loss measured by power meter with low reflection. From these data, an approximate curve of 5 th polynomial formula was derived by a least square method shown by the fitting curve in this



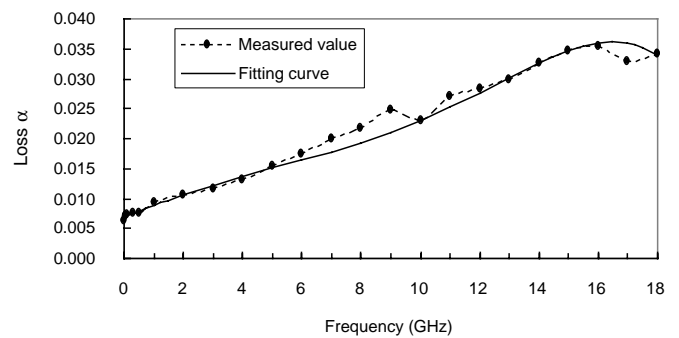
**Fig.2** Construction of the calorimeter (Side view of the inside jacket)

figure. This is used for the correction of RF power measured.

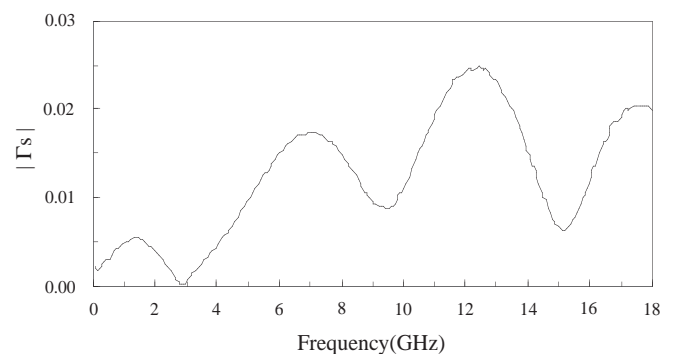
To minimize thermal capacity of the RF load, it has a special coupling nut which was separately manufactured, not using for the standard parts of the connector. The absorber (RF load) of RF power is a miniature termination with a built-in wire resistor (heater). It is of Manganin wire of about 1 kΩ wrapped around on the load. The reflection coefficient of the RF load is illustrated in **Fig. 5**.



**Fig.3** Reflection coefficient of the adiabatic line



**Fig.4** Loss of the adiabatic line



**Fig.5** Reflection of the RF load

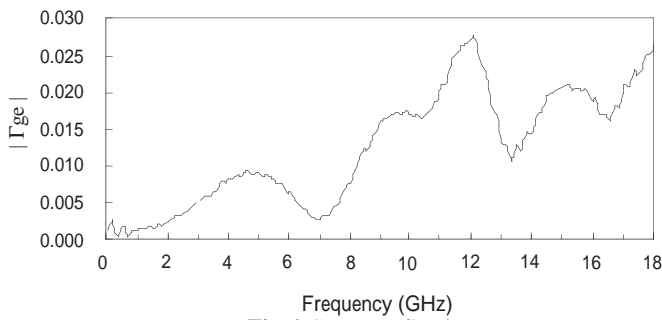
The cooling/detection part is fixed on the temperature reference block through a thermoelectric cooling element and two thermoelectric detecting elements. These elements are the same type of so called Peltier elements of 4 mm square and 3 mm height.

The stabilized signal source circuit consists of a synthesizer of 10 MHz -18 GHz, a power splitter and a monitor power meter. The signal source reflection is calculated from the following equation.

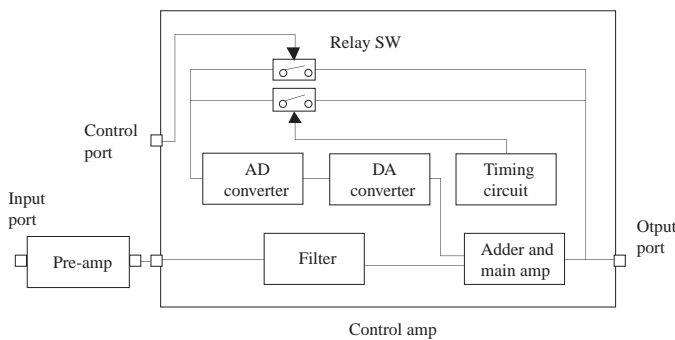
$$|\Gamma_{ge}| = \left| S_{11} - \frac{S_{13}S_{21}}{S_{23}} \right| \quad (4)$$

Each S parameter was measured using the network analyzer. The reflection coefficient of the signal source was calculated from the equation as shown in **Fig. 6**. It can be used for the uncertainty evaluation of the source mismatch for RF power measurement and DUT calibration.

The block diagram of the power control circuit to use for the calorimetric measurement is shown in **Fig.7**.



**Fig.6** Source reflection



**Fig. 7** Power control circuit

Pre-amplifier amplifies the output of the thermoelectric detecting element with 30 μ V full scale ( gain 3.3×10<sup>4</sup> ) and feeds back the output into the heater of the RF load through the control amplifier. The control amplifier consists of an AD and a DA converter (12 bits ), an adder/main amplifier and a filter. The relay switch is used as a switch which controls data from the AD converter. The data is transferred to the DA converter and is halt. This timing can be controlled by internal or external signal and the isothermal control comes to extremely stabilized<sup>9)</sup>.

These component were found to be sufficient to calorimetric RF power measurement and calibration of a DUT.

The parameter  $\alpha$  and  $q$  in the equation (3) is determined by experiments. In order to determine the parameter  $q$ , it is necessary to make precise correction considering the effect due to the excess heating of the adiabatic line. The results are shown in **Table 1**. Evaluation of them is scheduled to present in other report<sup>10)</sup>.

**Table 1** Basic characteristics of the calorimeter

Substitution coefficient k	1.0060
Excess heating ratio q	0.165
RF load resistance	49.875 Ω
Heater resistance	1.006 Ω
Responsivity for heater power	73.2 μV/mW
Responsivity for RF power	71.9 μV/mW
Responsivity for cooling power	61.0 μV/mW
Time constant for heater DC power	280s
Time constant for RF power	290 s
Time constant for cooling power	40 s

## §4 Measuring program

Three steps of the measurement are necessary. They are the measurement of the substitution coefficient  $k$  in the equation (3), the coupling ratio  $C_d$  in the equation (2) and the calibration factor  $K$  of a DUT. The computer controls and measures each part automatically through GP-IB and processes the data. The measurement procedure and the computer program of these pa-

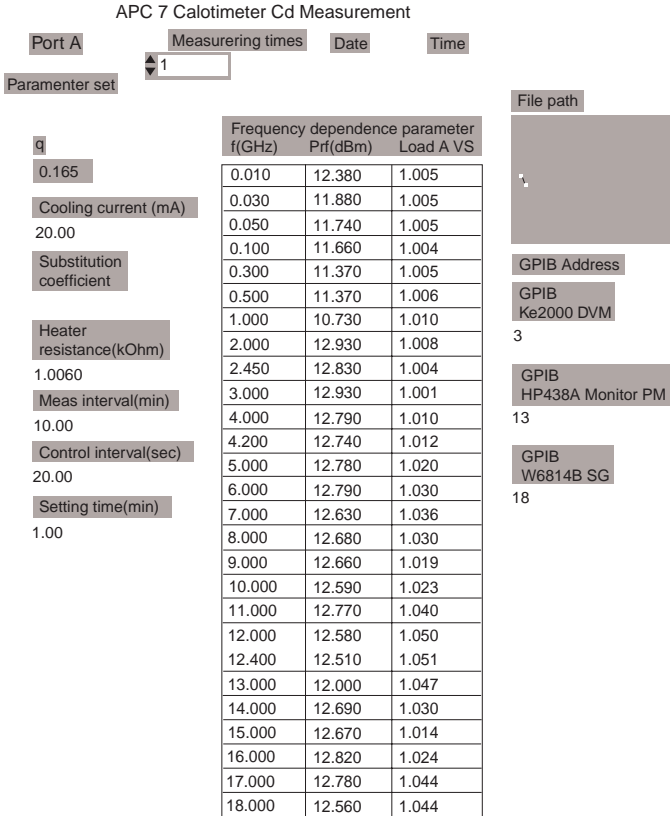
rameters are as follows.

! Substitution coefficient  $k$

Connecting a DC constant current source to the RF input port of the first adiabatic line, we measure  $k+$  and  $k-$  to the positive and negative DC current. At first we perform the isothermal control using the internal control function and wait until the control becomes sufficiently stable. Then we execute the program from the front panel of the program. The mean value  $k$  of them is used in the next step.

" Coupling ratio

On the front panel of **Fig.8**, measuring times, frequency, synthesizer output set level  $P_{rf}$  and other parameters are input including  $\alpha$  and  $q$ . Where, "Load A VS" means the VSWR of the RF load of port A. The program executes the isothermal control and measures RF power and monitor power, and determine the parameter  $C_d$ .



**Fig. 8** Front panel for  $C_d$  measurement

# Calibration factor of a DUT

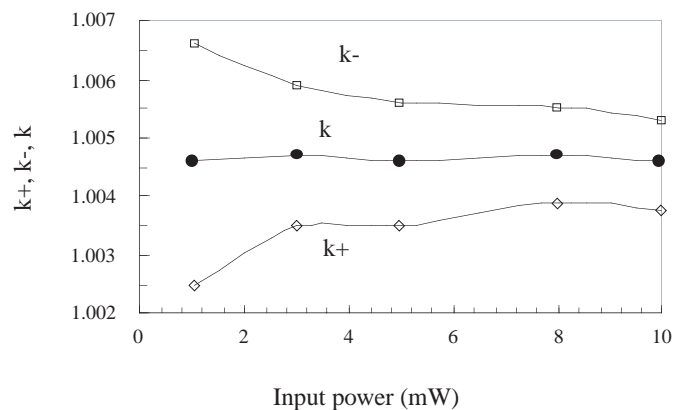
The calibration of a DUT is performed as follows. Removing the jacket, RF load and the cooling/detection part, we connect the DUT to the measuring port. On the front panel we set the frequency and the signal level as the same of the step " , and  $C_d$  for each frequency. Then we execute the comparison program.

In the step ! and " ,  $P_h$  is measured before and after either of the signal input ( DC or RF ) to compensate for the drift. These measurement results are recorded to either of the specified files.

## §5 Measurements

The basic characteristics of calorimetric port A is shown in Table 1. It is expected that the substitution coefficient has no level dependence following the theory<sup>7)</sup>. To confirm this,  $k$  was measured from 1 mW to 10 mW and is shown in **Fig.9**. As shown in this figure,  $k$  of the mean value of  $k+$  and  $k-$  is considered as constant in the whole area. The parameter  $q$  of the excess heat transfer ratio was determined by calorimetric measurements with a short at the RF load input connector and introducing AC or RF as described above<sup>10)</sup>.

In the measurement of  $C_d$ , 10 minutes are necessary for the bias measurement interval. For example, measurement of 18 points need about 6 hours. An example of the front panel which measured 39 points in the frequency range of 10 MHz-18 GHz is shown in **Fig.10**.



**Fig. 9** Example of measurement of the substitution coefficient

Where,  $P_h$  and  $P_{mr}$  is the heater bias power and the monitor power, respectively.  $P_{rf}$  and  $P_m$  is the calorimetric measured power and monitor power compensated for drift, respectively. RT and HUM is the room temperature and humidity, respectively.

An example of  $C_d$  measurement and calibration of thermo-type power meter were done and the results are shown in Fig.11. The measuring interval of the  $C_d$  measurement was 10 minutes and that of  $K$  was 1 minute. The standard deviation of  $C_d$  obtained by four times repetitive measurements was 0.0006-0.0013 and that of the  $K$  was 0.0001-0.002 .

In the uncertainty of measurement, there are various factors such as due to the substitution coefficient,

Measurement results							
f(GHz)	Ph(mW)	Prf(mW)	Pmr(mW)	Pm(mW)	Cd	RT(C)	HUM(%)
0.0000	15.6303	0.0000	0.0001	0.0000	0.0000	23.6426	39.2169
0.0100	5.4445	10.1837	10.0230	10.0228	1.0205	23.6530	39.2163
0.0000	15.6261	0.0000	0.0003	0.0000	0.0000	23.6409	38.7709
0.0300	5.4858	10.1384	10.0233	10.0231	1.0159	23.6228	38.9675
0.0000	15.6223	0.0000	0.0001	0.0000	0.0000	23.6175	39.0876
0.0500	5.5312	9.9717	9.9765	9.9761	1.0158	23.6537	38.3675
0.0000	15.6317	9.6128	9.1030	9.1027	0.0000	23.6373	38.9905
0.0000	15.5724	0.0000	0.0004	0.0000	0.0000	23.6527	38.2376
14.0000	4.9995	10.5701	9.9725	9.9722	1.0601	24.1160	34.5638
0.0000	15.5668	0.0000	0.0002	0.0000	0.0000	24.1368	33.9036
15.0000	4.9867	10.5784	9.9765	9.9763	1.0599	24.1870	34.0452
0.0000	15.5635	0.0000	0.0003	0.0000	0.0000	24.1877	33.3242
16.0000	4.9844	10.5764	9.9789	9.9787	1.0593	24.2105	32.7773
0.0000	15.5580	0.0000	0.0000	0.0000	0.0000	24.2029	32.9975
17.0000	4.9820	10.5715	9.9824	9.9824	1.0587	24.2133	32.3915
0.0000	15.5490	0.0000	0.0001	0.0000	0.0000	24.1974	32.3700
18.0000	4.9693	10.5779	9.9844	9.9844	1.0595	24.1870	32.9800
0.0000	15.5454	0.0000	0.0000	0.0000	0.0000	24.2022	32.5796

Fig. 10 Front panel of the results of  $C_d$  measurement

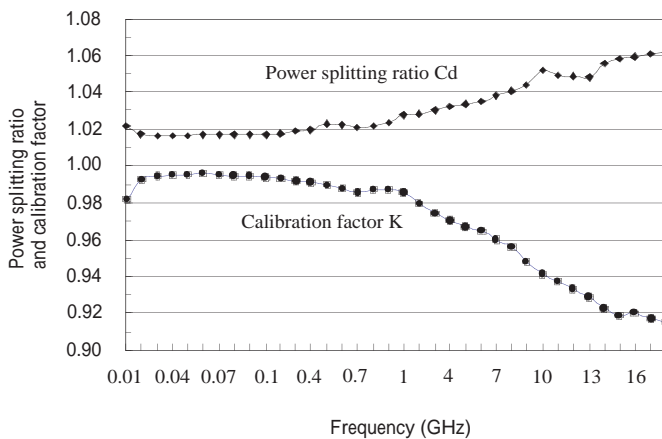


Fig.11 Example of  $C_d$  measurement and calibration

the source mismatch, the adiabatic line and so on. Evaluation of the uncertainty of the measurement is described in another paper of this bulletin.

## §6 Conclusion

An automatic calibration system for a broadband RF power meter was developed in the frequency range of 10 MHz -18 GHz for the 7 mm coaxial waveguide with APC7 connector. This system is composed of a twin type dry calorimeter, a broadband stabilized signal source and a controller. It measures the calibration factor of a DUT for the full band by direct measuring method of RF power. The design, fabrication, basic characteristics and calibration experiments were described. This system will be used as the standard for CCE GT-RF inter-comparison, JCSS and other calibrations.

We appreciate Mrs. Keiko Sato and Mr. Kyouhei Yamamura of the Japanese Quality Assurance Organization who cooperated with the development of this system.

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(Accepted January 31, 2000)