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Microwave Power Measurements: Standards and Transfer Techniques

Xiaohai Cui, Yu Song Meng, Yueyan Shan and Yong Li

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Abstract

In this chapter, precision power measurement, which is probably the most important area in RF and microwave metrology, will be discussed. Firstly, the background of RF and microwave power measurements and standards will be introduced. Secondly, the working principle of primary power standard (i.e., microcalorimeter) will be described, followed by the discussions of direct comparison transfer technique. Finally, there will be some discussions about the performance evaluation and uncertainty estimation for microwave power measurements.

Keywords: Direct comparison transfer, Microcalorimeter, Primary standard, RF and microwave power, Thermistor mount

1. Introduction

Recently, there are growing interests in higher frequency such as microwave and millimeter-wave applications, which is becoming a promising solution for satellite communications [1, 2] and millimeter-wave mobile backhauling [3]. For proper deployments of these applications and services, accurate and reliable signal power measurements are essential and important for system designers. Normally for the end users (i.e., system designers), microwave and millimeter-wave power measurements are highly relied on a conventional power detector and power meter combination or a spectrum analyzer. These measuring instruments have to be properly calibrated with traceability to the International System of Units (SI) for assuring the quality of measurement results as required by the industry.

As stated in ref. [4], the traceability of measuring instruments shall be achieved by means of an unbroken chain of calibrations or comparisons linking to relevant primary standards of the SI units of measurement as illustrated in **Figure 1**. The link to SI unit could be realized by a primary standard developed and maintained by a national metrology institute (NMI) such as the National Institute of Metrology (NIM) of China and the National Metrology Centre (NMC), A*STAR of Singapore. For RF, microwave, and millimeter-wave measurements and standards, power measurement has been recognized as one of the primary areas [5] and probably the most important research area by the NMIs. For simplicity in the rest of this chapter, microwave measurement will be synonymous to “RF, microwave, and millimeter-wave measurement.”

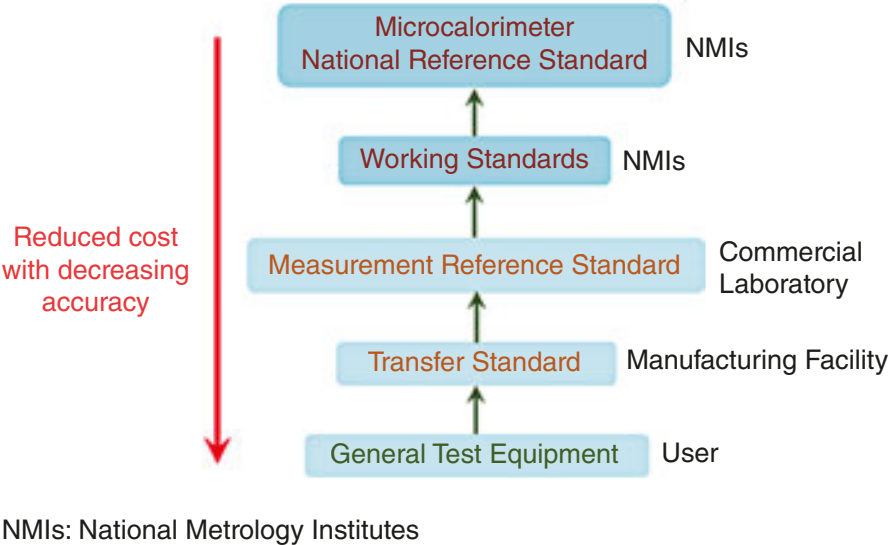


Figure 1. Typical traceability chain of RF, microwave, and millimeter-wave power measurements.

In the following, we will firstly give a background of microwave power measurements and standards. Secondly, a primary power standard (e.g., a microcalorimeter) will be discussed with recent developments at NIM, China. This will be followed by the discussions of the working principle of the microcalorimeter measurement system. The direct comparison transfer technique will be then introduced, together with some improvements at NMC, A*STAR of Singapore. Finally, performance evaluation and uncertainty estimation for microwave power measurements will be discussed.

2. Background of Power Measurements and Standards

Basically, microwave power can be measured by the combination of a power detector and a power meter, as shown in **Figure 2**. The power detector is a key instrument for power measurements, and its function is to convert high-frequency (i.e., RF, microwave, and millimeter-wave or higher) power to a direct current (DC) or low-frequency signal that a power

meter can measure with a display. Different working principles and fabrication techniques have led to several power detectors that have been widely used in commercial applications.

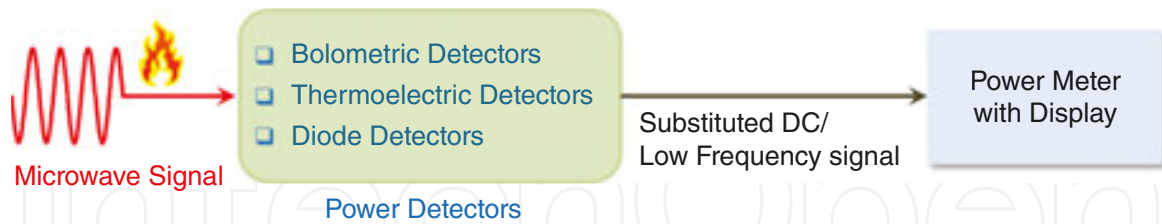


Figure 2. Microwave power measurements in the combination of a power detector and a power meter.

2.1. Commercial Power Detectors

Three main types of power detectors have been commercially available, which are designed and based on the bolometric element, thermoelectric element, and diode. The respective working principles behind are through

1. substituting DC power for RF power (bolometric type),
2. representing a thermally generated voltage for RF power (thermoelectric type), or
3. using the rectification property to convert RF power to DC voltage (diode type).

It is noted that each type of power detector indicated above has its own strengths and weaknesses for its application. In the early days [5], the diode detector was very sensitive to ambient temperature and also with a poor linearity, and therefore, it was rarely adopted as a transfer standard. Most of the NMIs have been continuously using bolometric detectors (i.e., bolometers) as transfer standards, since they are very nearly linear when used with a primary power standard (e.g., a microcalorimeter [6]) through the DC substitution technique. Bolometric detectors can also offer an extremely high long-term stability with a very low measurement uncertainty [7, 8].

However, a bolometric detector normally has a narrow dynamic range and limited power capability (e.g., with a power range from 10 μ W to 10 mW [7]). Additionally, its productions have been discontinued, accompanying a new industry production trend toward other types of power sensors (e.g., diodes and thermocouples). Some NMIs therefore have attempted to use thermoelectric detectors (e.g., thermocouples) as the transfer standards [9], which are linear with a better sensitivity and dynamic range. Performance comparison between bolometric and thermoelectric sensors has recently been reported in ref. [10] using the same microcalorimeter. The results revealed that the two power standards (bolometric and thermoelectric sensors) in the comparison can be considered equivalent.

In the following, the bolometric detector as the transfer standard will be introduced, since it has been widely used by most of the NMIs including NIM of China and NMC, A*STAR of Singapore. Its calibration using a microcalorimeter will be focused upon and described.

2.2. Reference Power Standard: Bolometer

Bolometers have a very high reliability and have been used as the reference power standards in most of the NMIs, together with a microcalorimeter. A bolometer consists of a small temperature-sensitive resistor. It is operated by changing its own resistance following a change in its temperature resulted from the incident microwave power being dissipated in the bolometric element.

Two types of bolometers have been commonly used, namely, barretter and thermistor. The barretter is a thin metal wire with a positive temperature coefficient of resistance, and the thermistor is a small bead of semiconductor material with a negative temperature coefficient of resistance [11]. It is noted that the thermistor is more sensitive than the barretter due to a much greater temperature coefficient, but it has a slower response time due to its larger thermal time constant [12].

The thermistor is therefore more popularly used. Typically, a thermistor bead has a diameter of around 0.05–0.5 mm with a small-size (diameter of 15–100 μm) metal wire embedded inside. A waveguide or coaxial termination that houses a thermistor with an internal matching circuit to obtain specified impedance conditions (e.g., 100 Ω or 200 Ω) with appropriate DC bias power applied [11] is called a thermistor mount. The schematic diagram of a popular type of waveguide thermistor mount is shown in **Figure 3**, and some samples of waveguide thermistor mounts used at NIM, China, are shown in **Figure 4**.

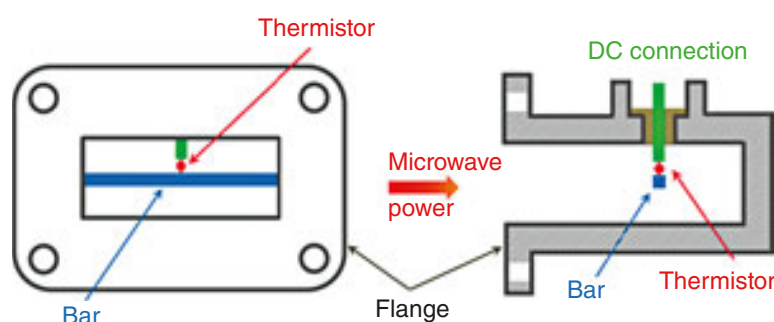


Figure 3. One popular type of waveguide thermistor mount.



Figure 4. Waveguide thermistor mounts.

2.3. Primary Power Standard: Microcalorimeter

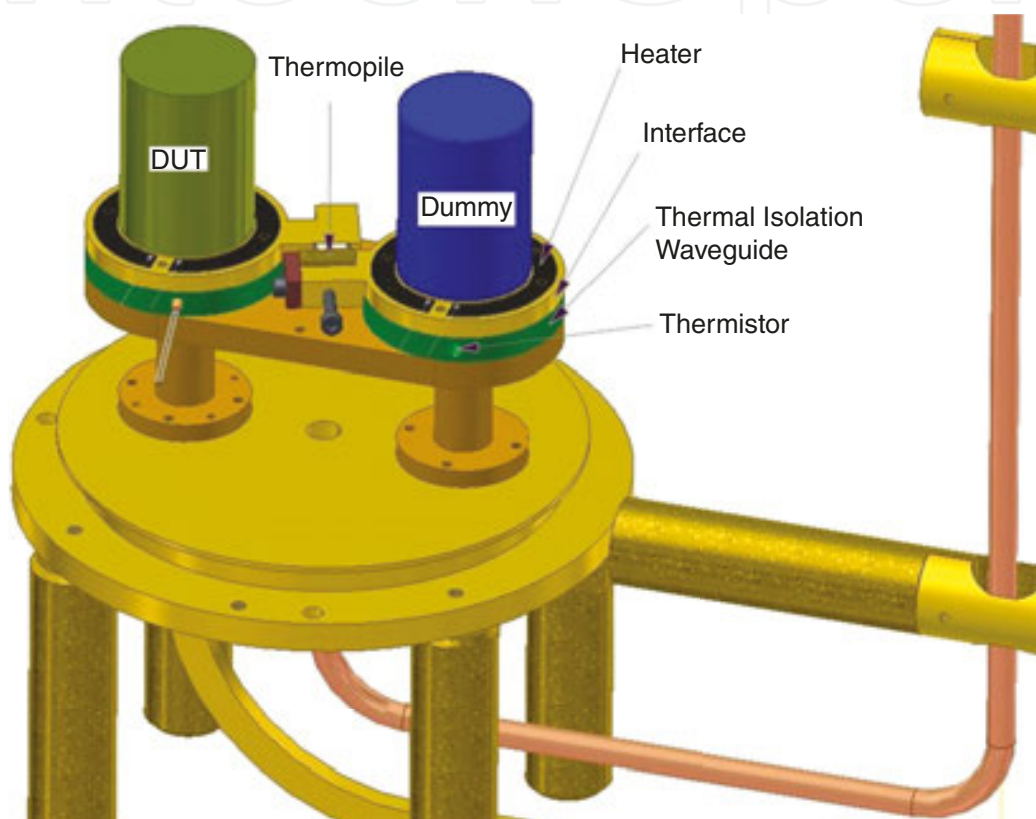


Figure 5 presents the design and configuration of a waveguide microcalorimeter, which is China's national primary power standard developed and maintained at NIM, China, for the thermistor mount [device under test (DUT) in this case] measurements [15–18] through the DC substitution technique (i.e., applied microwave power is compensated by an appropriate reduction of DC power). As shown in **Figure 5**, the design of a waveguide microcalorimeter at NIM, China, is based on a twin-line structure with a symmetrically located inactive mount (i.e., a “dummy” thermistor mount) as the temperature reference. A thermopile is attached in between to monitor the temperature difference, when the microcalorimeter is in operation with a thermistor mount (DUT). With the same DUT and dummy mounts, nearly the same thermal transmission paths could be achieved and therefore produce almost identical response to the

ambient temperature at both the terminals of the thermopile. This twin-line design makes the microcalorimeter less affected by the ambient temperature. More specifically, it could effectively reduce the influence of a long-term ambient temperature drift on the measurement results.

The core part of the microcalorimeter as shown in **Figure 5** consists of a base extension, two thermal isolation sections (TIS), and two interface plates. The DUT is attached to a standard waveguide flange on the interface plate with screws that pass through all the three core components. The TIS is about 6 mm thick and is made of gold-coated ABS plastic so that the waveguide section has little loss. A thermistor has been embedded into the TIS for monitoring its temperature rise due to unexpected power consumption within the thermal isolation waveguide. A sample of fabricated WR-22 waveguide microcalorimeter at NIM, China, is shown in **Figure 6**.

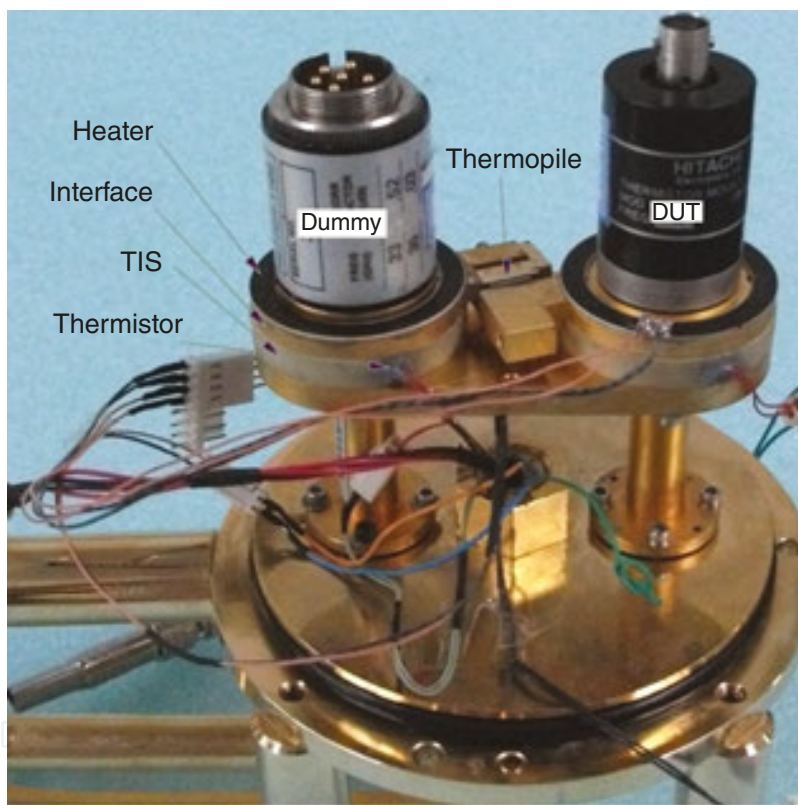


Figure 6. Fabricated WR-22 waveguide microcalorimeter at NIM, China.

3. The Working Principle of Microcalorimeter

The microcalorimeter is used to measure the effective efficiency η_e of a thermistor mount which serves as the reference standard for power measurements. The effective efficiency η_e of a bolometer unit (e.g., a thermistor mount) is defined as the ratio of the changes in the DC-

substituted power P_{sub} to the total microwave power P_{rf} dissipated within the bolometer unit, as specified in ref. [11]. That is,

$$\eta_e = \frac{P_{sub}}{P_{rf}}. \quad (1)$$

It is noted that, in practice, the effective efficiency η_e of a thermistor mount is determined using the DC substitution technique with a microcalorimeter, in conjunction with a self-balancing bridge circuit.

3.1. DC Substitution Technique

The DC substitution technique has been implemented through automatically reducing the DC bias power to keep the operating resistance of a thermistor constant, when the microwave power is applied to the thermistor mount. Ideally, if the applied microwave power is totally absorbed by the thermistor element and the thermistor also has the same thermal reaction for DC and microwave power, $P_{sub} = P_{rf}$. Thereby, $\eta_e = 1$.

However, practically, there are some existing losses in the input transmission line, the mount structure, and others. For example, as shown in **Figure 7**, some unexpected power consumptions could be on the wall of the thermistor mount (P_w) and within the thermal isolation waveguide (P_i), besides the net power P_{rft} dissipated on the thermistor bead. It is noted that practically the net power P_{rft} is very difficult/impossible to be measured and is represented by the compensated DC power (i.e., DC-substituted power P_{sub}). These effects can result in a measurement error, which is normally characterized as the mount efficiency. Moreover, the thermistor bead has a different thermal reaction and power distribution for DC and microwave powers and can cause a microwave-to-DC (or RF-to-DC) substitution error. Both the mount efficiency and the microwave-to-DC substitution error shall be considered in the correction factor g of a microcalorimeter for accurate effective efficiency determination.

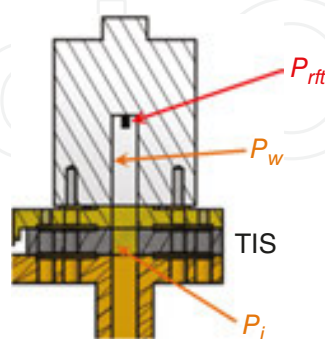


Figure 7. Main power absorptions when calibrating a thermistor mount using a microcalorimeter.

The DC substitution requires a self-balancing bridge circuit to work with the thermistor mount for keeping its operating resistance R_T constant, when the microwave power is applied.

Figure 8 shows a typical self-balancing bridge circuit for maintaining R_T . The initial resistance R_T of a thermistor is normally at $200\ \Omega$ (or $100\ \Omega$ for different types of thermistor mounts) with a DC bias. When the microwave power is fed to the thermistor, R_T will change due to the temperature rising of the thermistor. The DC bias power has to be reduced to balance the bridge circuit. It is noted that the reduced amount of DC-biased power is proportional to the microwave power P_{rf} applied onto the thermistor bead.

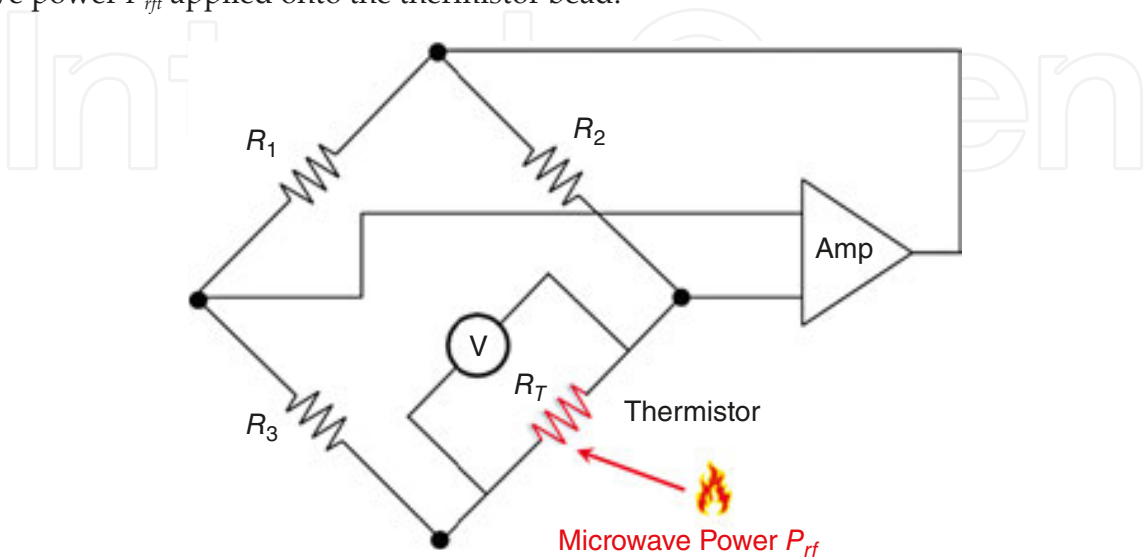


Figure 8. An example of a self-balancing bridge circuit for monitoring the resistance change in a thermistor mount.

3.2. Operation of a Microcalorimeter

A Type IV power meter has been fabricated at NIM, China, for realizing the DC substitution technique with a self-balancing bridge circuit inside. It works with the thermistor mount in a closed loop to keep R_T constant. The internal circuit of the NIM-manufactured Type IV power meter for calibrating the thermistor mount is shown in **Figure 9**.

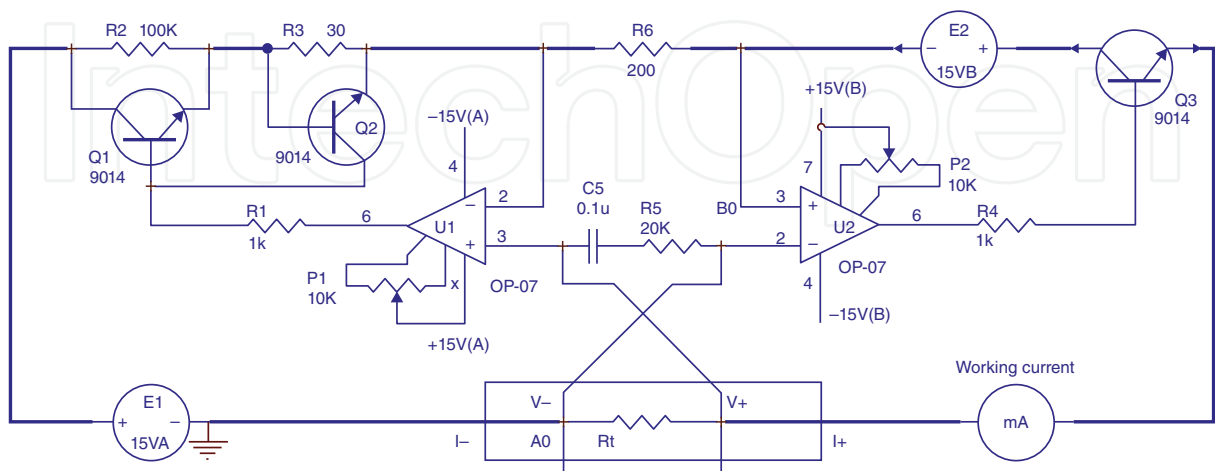


Figure 9. Internal circuit diagram of the NIM-manufactured Type IV power meter for measuring the thermistor mount.

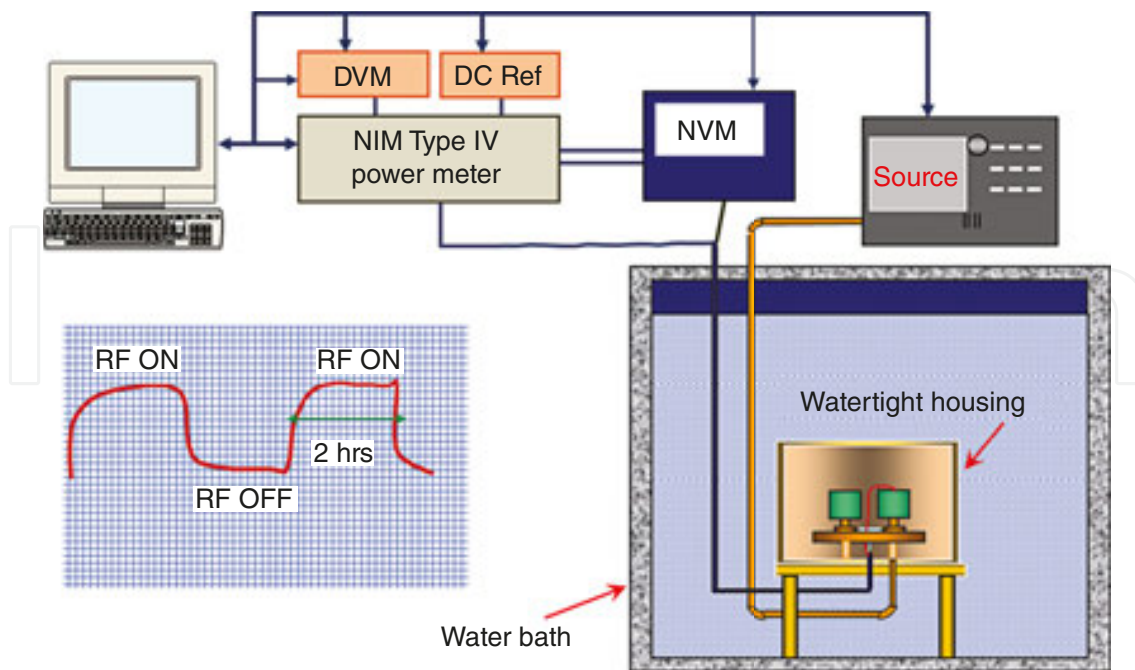


Figure 10. Schematic diagram for microcalorimeter measurements inside a water bath.

Figure 10 presents a complete operation setup for thermistor mount measurements and calibrations using a microcalorimeter at NIM, China. The microcalorimeter is sealed within a watertight housing and then is placed inside a water bath. The water bath has a very good thermal stability with a temperature fluctuation of less than 1 mK. During the measurements, signal source, digital voltmeter (DVM), nanovoltmeter (NVM), DC reference (DC Ref), and Type IV power meter were controlled by a computer for automation.

The measurement system is used to determine the DC bias voltages (V_1 and V_2) and thermopile outputs (e_1 and e_2) when the applied microwave power is off/on and the system reaches the thermal equilibrium. A typical output curve from the thermopile is also shown in **Figure 10** as a reference when the applied microwave power is off/on. With V_1 , V_2 , e_1 , e_2 , and correction factor g of a microcalorimeter, the effective efficiency η_e can be determined.

3.3. Measurement and Calibration Model

From the definition, the effective efficiency η_e of the thermistor mount is

$$\eta_e = \frac{P_{sub}}{P_{rf}} = \frac{P_{sub}}{P_{sub} + P_{dw}}. \quad (2)$$

Here, the total microwave power P_{rf} dissipated within the thermistor mount includes the DC-substituted power P_{sub} on the thermistor bead and the total loss P_{dw} (including the loss P_w on the wall of the thermistor mount and some portion of unsubstituted power). The DC-substituted power P_{sub} can be estimated through the DC bias voltages V_1 and V_2 , as

$$P_{Sub} = \frac{V_1^2 - V_2^2}{R}. \quad (3)$$

The loss P_{dw} contributes to the portion of thermopile output change ($\Delta e = e_2 - e_1$) due to the temperature rising. The thermopile output change Δe has the following relationship:

$$\Delta e \propto (P_{dw} + cP_i). \quad (4)$$

The coefficient c is the weighted thermal factor due to the loss P_i within the thermal isolation waveguide onto the thermopile output. If the loss is uniformly distributed along the axial direction of the thermal isolation waveguide (typical case), $c = 0.5$.

Taking into consideration all the contributions from heat dissipated in different locations (such as the mount wall, TIS) of a microcalorimeter into its correction factor g , the effective efficiency η_e of thermistor mount at each frequency of interest can be calculated using the following recommendation [14]:

$$\eta_e = g \frac{1 - \left(\frac{V_2}{V_1}\right)^2}{\frac{e_2}{e_1} - \left(\frac{V_2}{V_1}\right)^2} = g\eta_{e,unc}. \quad (5)$$

Here, $\eta_{e,unc}$ is the uncorrected effective efficiency, and g is the correction factor, which is the most important characteristic of a microcalorimeter. Several different techniques have been proposed in refs. [17–20] for evaluating the correction factor g , in order to determine the effective efficiency of the reference standard, thermistor mount, accurately. It is noted that sometimes the calibration factor K of the thermistor mount is of interest for applications. The calibration factor K can be derived from the effective efficiency η_e as

$$K = \eta_e (1 - |\Gamma|^2). \quad (6)$$

Here, Γ is the input reflection coefficient of the thermistor mount.

4. Transfer Technique: Direct Comparison

The parameter of a reference power standard such as a thermistor mount can be transferred to the DUT sensor by means of the direct comparison transfer technique, which was proposed and summarized by the National Institute of Standards and Technology (NIST) of USA [21,

22]. **Figure 11** presents a basic idea of the direct comparison transfer for waveguide microwave power sensor calibration.

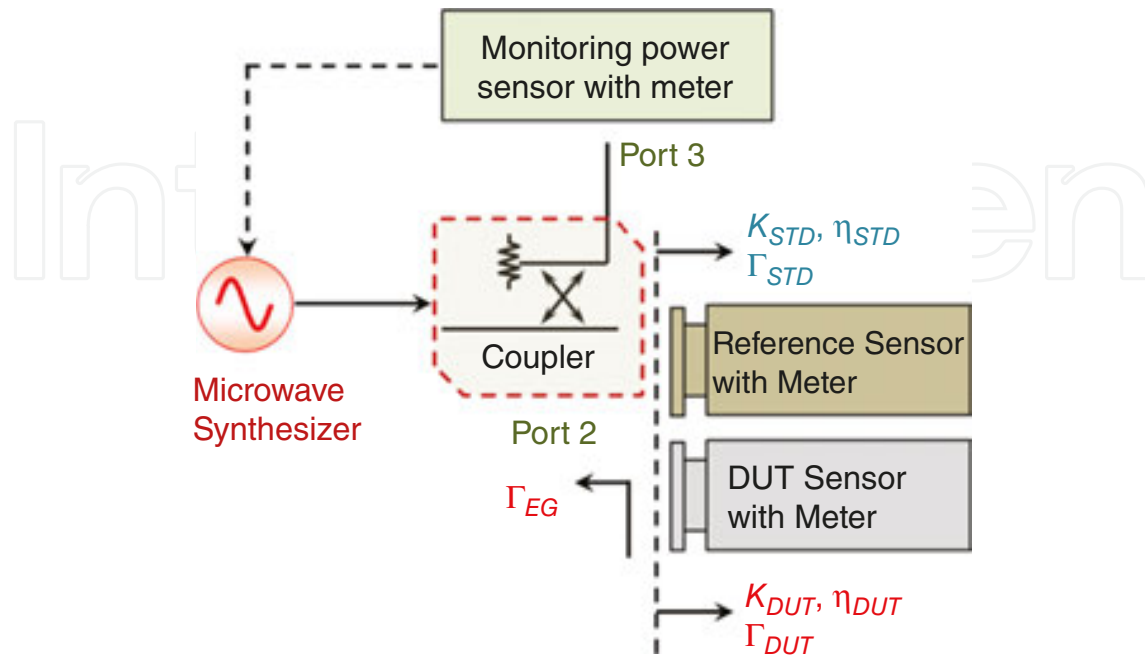


Figure 11. Calibration of a waveguide power sensor by means of direct comparison transfer using a coupler.

The system consists of a microwave synthesizer and a three-port directional coupler which is used to minimize the source mismatch [23]. As shown in **Figure 11**, a monitoring power sensor with a meter is connected to Port 3 of the coupler. The effective efficiency η_{DUT} and the calibration factor K_{DUT} of a DUT sensor are measured by alternately connecting a reference power standard (e.g., a thermistor mount with the effective efficiency η_{STD} and the calibration factor K_{STD}) and the DUT to Port 2 of the coupler. For the setup shown in **Figure 11**, the connectors of the DUT and the reference standard are kept the same. It is noted that for coaxial application, the coupler shall be replaced using a three-port power splitter.

The calibration factor K_{DUT} of the DUT sensor can be determined through

$$K_{DUT} = K_{STD} \times \frac{P_{DUT}}{P_{STD}} \times \frac{P_{3STD}}{P_{3DUT}} \times \frac{|1 - \Gamma_{DUT} \Gamma_{EG}|^2}{|1 - \Gamma_{STD} \Gamma_{EG}|^2}. \quad (7)$$

Here, P_{DUT} and P_{3DUT} are the powers measured at Port 2 using the DUT sensor and that at Port 3 using a monitoring power sensor, respectively. P_{STD} and P_{3STD} are the powers measured at Port 2 using the reference standard (e.g., a thermistor mount) and that at Port 3 using the same monitoring power sensor. Γ_{STD} is the input reflection coefficient of the reference standard, and Γ_{DUT} is the input reflection coefficient of the DUT. Γ_{EG} is the equivalent source match term of Port 2 [8] and equal to

$$\Gamma_{EG} = S_{22} - \frac{S_{21}S_{32}}{S_{31}}, \quad (8)$$

where S_{ij} ($i, j = 1, 2$, or 3) are the scattering parameters (S-parameter) of the directional coupler. A more detailed description of eq. (7) can be obtained in refs. [24, 25], and the derivation of eq. (8) can be found in ref. [6].

However, sometimes, a DUT sensor has an unmatched connector with the reference standards, and then an adaptor has to be used. Some measurement models with an adaptor at DUT/reference standards have been proposed in refs. [25–27] and will be briefly introduced below.

4.1. Calibration Scenario with an Adaptor before Reference Standard

This is the application scenario where an adaptor has been connected between the reference standard and Port 2 of the coupler, while the DUT sensor is alternatively connected to Port 2 directly. The calibration factor K_{DUT} of the DUT sensor can be calculated with

$$K_{DUT} = K_{STD} \times \frac{P_{DUT}}{P_{STD}} \times \frac{P_{3STD}}{P_{3DUT}} \times \left| \frac{S_{21A}(1 - \Gamma_{DUT}\Gamma_{EG})}{1 - \Gamma_{STD}S_{22A} - \Gamma_{EG}\Gamma_{A-STD}} \right|^2. \quad (9)$$

Here, $\Gamma_{A-STD} = S_{11A} + \Gamma_{STD}S_{21A}S_{12A} - \Gamma_{STD}S_{22A}S_{11A}$, and S_{lmA} is the S-parameter of adaptor A, and $l, m = 1$ or 2 . **Figure 12** presents a typical measurement setup when a coaxial-to-waveguide adaptor has been used before a waveguide reference standard (a thermistor mount as shown in **Figure 12** (a)).

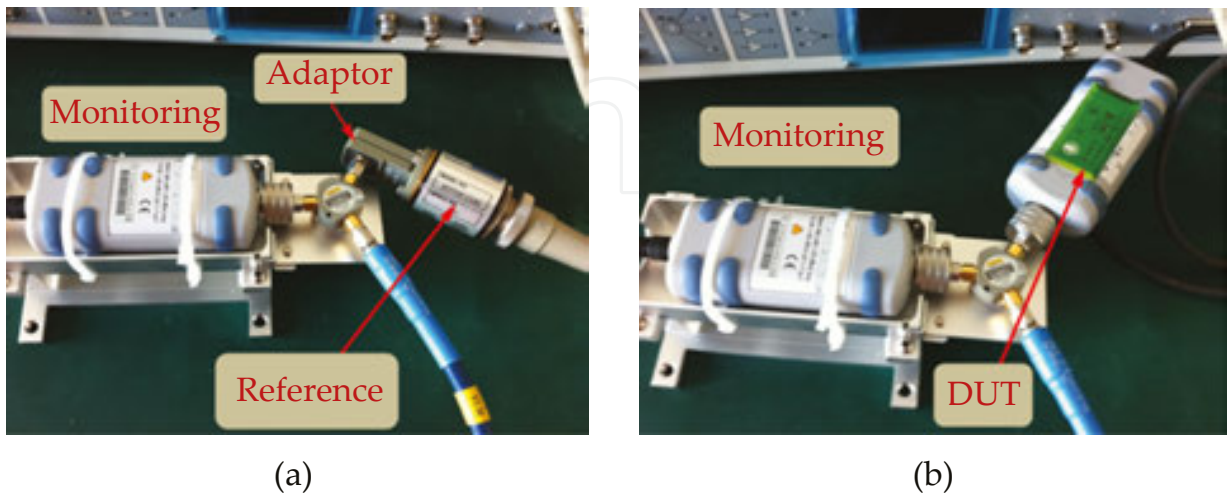


Figure 12. Calibration of a DUT sensor by means of direct comparison transfer with an adaptor before the reference standard.

4.2. Calibration Scenario with an Adaptor before DUT Sensor

This is the application scenario where an adaptor has been connected between the DUT sensor and Port 2 of the coupler, while the reference standard is alternatively connected to Port 2 directly. The calibration factor K_{DUT} of the DUT sensor can be calculated with

$$K_{DUT} = K_{STD} \times \frac{P_{DUT}}{P_{STD}} \times \frac{P_{3STD}}{P_{3DUT}} \times \left| \frac{1 - \Gamma_{DUT} S_{22A} - \Gamma_{EG} \Gamma_{A-DUT}}{S_{21A} (1 - \Gamma_{STD} \Gamma_{EG})} \right|^2. \quad (10)$$

Here, $\Gamma_{A-DUT} = S_{11A} + \Gamma_{DUT} S_{21A} S_{12A} - \Gamma_{DUT} S_{22A} S_{11A}$. The mathematical model [eq. (10)] was previously derived using signal flow graphs together with the non-touching loop rule analysis in ref. [25]. It was later comparatively investigated in ref. [27] through the analysis of physical measurement processes. A consistent mathematical model has been observed.

The proposed model was successfully used to calibrate a high-sensitivity (lower power range) power sensor with an attenuator (the attenuator can be treated as a two-port adaptor with high loss) between the DUT and Port 2 of the coupler in ref. [27]. Good performance has been achieved referring to the data from the manufacturer.

5. Performance Evaluation and Uncertainty Estimation

In this section, the evaluation of measurement uncertainty is briefly introduced with the *Guide to the Expression of Uncertainty in Measurement* (GUM) [28]. The GUM method has been accepted and used in most of the current routine calibration works at NMIs or the standards laboratories. This is followed by an example of calibrating waveguide thermistor mounts with uncertainty evaluation in an international comparison.

5.1. Estimation of Measurement Uncertainty

To evaluate the measurement uncertainty, the GUM shall be followed. According to the GUM, there are two methods to evaluate the standard uncertainty $u(x_i)$ associated with the physical quantity x_i in the measurements, namely, *Type A Evaluation* and *Type B Evaluation*.

Type A Evaluation is a method of evaluating the standard uncertainty through the statistical analysis of a series of observations. It is normally referred to as “repeatable” measurement uncertainty. *Type B Evaluation* is a method of evaluating the standard uncertainty from other information including previous measurement data, specifications from manufacturers, data provided in calibration and other certificates, and uncertainties assigned to reference data taken from handbooks.

For evaluating the uncertainty of a measurand y from the standard uncertainty information of other physical quantities (x_1, x_2, \dots, x_N) with $y = f(x_1, x_2, \dots, x_N)$, combined standard uncertainty $u_c(y)$ associated with y is adopted. According to the *Law of Propagation of Uncertainty* (LPU) in the GUM [28], $u_c(y)$ can be estimated from the standard uncertainties of x_1, x_2, \dots, x_N , as

$$u_c(y) = \sqrt{\sum_{i=1}^N \left[\frac{\partial f}{\partial x_i} \right]^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)}, \quad (11)$$

where $u(x_i, x_j)$ is the covariance between x_i and x_j .

The expanded uncertainty U , which defines an interval about the result of a measurement that may be expected, can be estimated through $U = ku_c$. Here, k is the coverage factor and equal to 2 for a one-dimensional physical quantity at a level of confidence of approximately 95% assuming a Gaussian distribution. However, for a complex-valued physical quantity (e.g., S-parameter), the coverage factor k for 95% coverage probability is around 2.45 [29, 30].

5.2. Performance Evaluation in an International Comparison

CCEM.RF-K25.W Key Comparison: The precision measurement capabilities of NIM-fabricated WR-22 microcalorimeter have been validated and demonstrated in a key comparison (CCEM.RF-K25.W) on high-frequency power in the frequency range 33–50 GHz. The comparison is an exercise to establish the metrological equivalence of signatory NMIs' standards as stated in the Mutual Recognition Arrangement (MRA) of the Bureau International des Poids et Mesures (BIPM).

In the CCEM.RF-K25.W comparison, the effective efficiency and calibration factor of the travelling standards (Hughes Model 45772H-1100) as shown in **Figure 13** were compared. The effective efficiency of the travelling standard at each frequency of interest was determined by measuring the heating of mount in the microcalorimeter during the DC substitution. As introduced previously, a Type IV power meter was used as a bolometer bridge. The correction factor g of NIM's microcalorimeter was characterized through the measurements where a foil short was inserted between the test port and the DUT in the microcalorimeter [16].



Figure 13. Participation in the international key comparison, CCEM.RF-K25.W.

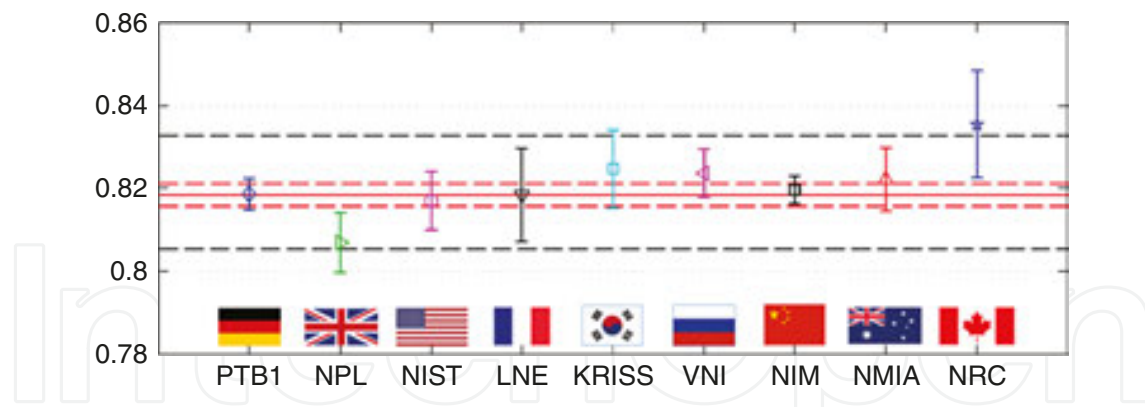


Figure 14. Calibration factor for the travelling standard Hughes Model 45772H-1100 (SN 216) at 33.0 GHz [31].

Figure 14 presents the measured calibration factor K for the travelling standard Hughes Model 45772H-1100 (SN 216) at 33.0 GHz. From the results shown in **Figure 14**, it can be observed that the NIM's microcalorimeter has a good measurement capability, and very good equivalence has been achieved referring to the results reported by other NMIs. An example of NIM uncertainty budget at 33.0 GHz is shown in Table 1 as a reference.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/Type	Sensitivity coefficient c_i	Uncertainty contribution $c_i u(X_i)$	DOF ν_i
DC voltage ratio	0.8689	0.00002	Gaussian/Type B	1.5	0.00003	50
Thermal voltage ratio	1.0172	0.0004	Gaussian/Type B	0.93	0.0004	50
Correction factor g	1.0035	0.0036	Gaussian/Type B	0.85	0.003	50
Repeatability	0.8850	0.0009	Gaussian/Type A	0.96	0.0009	3
$ \Gamma $	0.2778	0.0025	Gaussian/Type B	0.46	0.001	50
K	0.8196	0.0033				$\nu_{\text{eff}} = 27$

Table 1. An example of NIM uncertainty budget at 33.0 GHz [31].

6. Summary

In this chapter, we mainly focused on the introduction of microwave power measurements and standards. Primary power standards (e.g., microcalorimeter) and reference standards (e.g., thermistor mounts) have been discussed. Some recent developments of the waveguide microcalorimeter at NIM, China, and further applications of the direct comparison transfer technique at NMC, A*STAR of Singapore, have been reported. This is followed by an introduction of uncertainty evaluation for calibrating a WR-22 waveguide thermistor power sensor during an international comparison.

Furthermore, we have attempted to calibrate a WR-15 (50–75 GHz) waveguide thermistor mount using the direct comparison transfer technique [32]. Good performance has been

observed preliminarily. Further improvement works have been planned and will be carried out in the near future.

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