

# An Improved Design and Simplified Evaluation Technique for Waveguide Microcalorimeter

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**Abstract**— An improved design and simplified evaluation technique for waveguide microcalorimeter is presented in this paper. The design is based on a traditional twin-line microcalorimeter for calibrating thermistor mounts but with a novel modification proposed. In the improved design, another thermistor is added to measure the temperature change of the thermal isolation waveguide section. A simplified evaluation method is also proposed to minimize the S-parameter measurements for obtaining the effective efficiency of the mount. The measurement model and its detailed derivation are discussed. The capability of the improved design and proposed evaluation technique has been assessed through a recent CCEM key comparison.

**Index Terms**—microcalorimeter, microwave power, millimeter-wave power, primary standards

## I. INTRODUCTION

MICROCALORIMETERS have been accepted as the basis of primary standards for RF, microwave and millimeter-wave power measurements within the National Metrology Institutes (NMIs) [1-6]. They are used to measure the effective efficiency of bolometric transfer standards such as the thermistor mount. The key parameter of power transfer standards, *effective efficiency*, needs to be accurately evaluated with an associated uncertainty. The effective efficiency is defined as the ratio of the change in the direct current (DC) power (or DC substitution power) to the absorbed RF, microwave and millimeter-wave power applied to the transfer standards. In this paper, any transfer standard discussed is a commercial thermistor power sensor or ‘mount’ and will be referred to as a Device Under Test (DUT). For simplicity, RF measurement will be synonymous for “RF, microwave and millimeter-wave measurement” in the rest of the paper.

The effective efficiency of a mount is determined by

measuring the temperature differences associated with the DC power absorption and the RF power absorption, using a microcalorimeter. The important parameter is the correction factor  $g$  of the microcalorimeter, which describes the relative response of its thermopile to the RF and DC powers [7-8] when the microcalorimeter is immersed in a temperature-controlled water bath.

At each frequency, the system is allowed to stabilize and the effective efficiency is calculated as follows [3],

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

Here  $V_1$  and  $e_1$  are the output voltages of the power meter and thermopile with only the DC applied to the mount, and  $V_2$  and  $e_2$  are the same voltages with both the RF and DC applied. The correction factor  $g$  can be determined from the measurements when the transmission line in the microcalorimeter is terminated by a foil short [7]:

$$g \approx 1 + \frac{1 + |\Gamma_M|^2}{1 - |\Gamma_M|^2} \left( \frac{\Delta e_{FS}}{k_1 P_{IFS} (1 + |\Gamma_{FS}|^2)} - \frac{1 - |\Gamma_{FS}|^2}{1 + |\Gamma_{FS}|^2} \right), \quad (2)$$

where  $\Gamma_M$  and  $\Gamma_{FS}$  are the reflection coefficients of the thermistor mount (DUT) and the foil short,  $\Delta e_{FS}$  is the corresponding thermopile voltage change, and  $k_1$  is a proportionality constant that depends on the fraction of power flowing through the thermopile and the thermopile sensitivity [7].  $P_{IFS}$  is the incident RF power at the foil short which can be determined using a directional coupler. The accurate determination of  $P_{IFS}$  relies on the knowledge of reflection coefficients as follows:

$$P_{IFS} \propto \frac{1}{1 - |\Gamma_S|^2} \frac{|1 - \Gamma_{GE} \Gamma_S|^2}{|1 - \Gamma_{GE} \Gamma_{FS}|^2}. \quad (3)$$

where  $\Gamma_{GE}$  is the equivalent source reflection of the coupler [9], and  $\Gamma_S$  is the reflection coefficient of a power standard. From equations (1) to (3), it is obvious that the traditional method to get the DUT’s effective efficiency must use the side-arm calibration measurements with alternative connection of the DUT and the foil short, and therefore several reflection coefficients have to be measured.

In order to simplify the measurement procedure and then

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reduce the sources of measurement uncertainty, a temperature sensor (a thermistor) has been proposed to be added into the microcalorimeter to measure the temperature change of its thermal isolation section which is indicative of the RF power loss in that section and how much the DUT's effective efficiency measurements are affected.

In addition to the evaluation technique recommended by the National Institute of Standards and Technology (NIST), USA [3], a simplified evaluation method which was briefly introduced in [10] will be described in detail for obtaining the effective efficiency of a DUT in this paper. The advantage of this evaluation technique to the improved microcalorimeter design is to reduce the S-parameter measurements [11] for the reflection coefficients as shown in (3). Correspondingly, the measurement procedures can be simplified significantly.

In the rest of this paper, the proposed design is presented in Section II, with theoretical background discussed. In Section III, some improvements into the key part of a newly fabricated microcalorimeter, *thermal isolation waveguide section (TIS)*, is highlighted. This is followed by some performance evaluation in Section IV. Finally, conclusions are given in Section V.

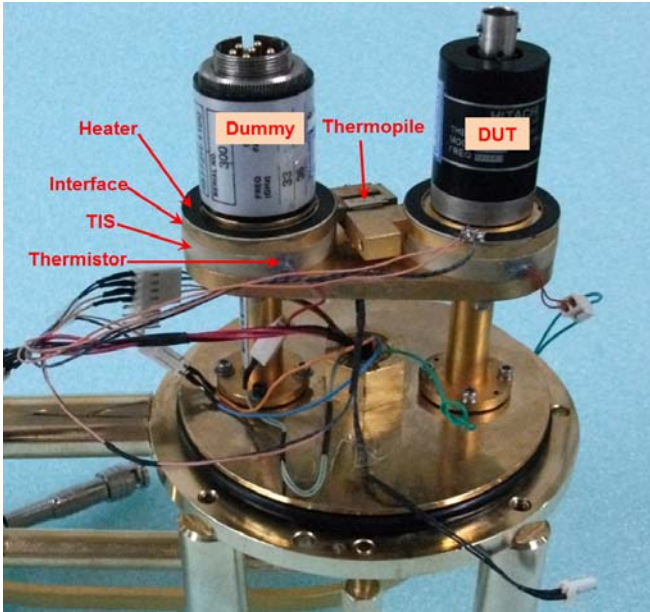


Fig. 1. Picture of a WR-22 microcalorimeter assembled at NIM, China [10].

## II. THE PROPOSED MICROCALORIMETER DESIGN

A WR-22 microcalorimeter that will be the national waveguide power standard of China was designed and fabricated at the National Institute of Metrology (NIM), China. Fig.1 shows an assembled WR-22 microcalorimeter which covers the frequency range of 33 GHz to 50 GHz. It is noted that the microcalorimeter is configured for a standard effective efficiency measurement that will be referred as a DUT measurement as mentioned above.

As shown in Fig.1, the core part of the microcalorimeter consists of a base extension, two TISs and two interface plates (Interface). The DUT is connected by a WR-22 flange on the

interface plate with screws that pass through all three core components. The TIS is about 6 mm thick and is made of gold-plated Acrylonitrile Butadiene Styrene (ABS) plastic so that the waveguide section has low losses.

### A. Improved Design

Similar to the new WR-15 microcalorimeter at NIST [3, 5], the microcalorimeter design in this work is also based on a twin-line structure and thermopile. However, an additional “O” shaped heater (different from [3, 5]) is attached to each interface plate, and two thermistors (used as temperature sensors) are embedded into the two TISs. A thermopile measures the temperature difference between the DUT and a symmetrically located sensor that is inactive (denoted as Dummy in Fig.1). A watertight housing is used, and the microcalorimeter measurements are taken with the apparatus submerged into a water bath that has temperature fluctuations of less than 1 mK.

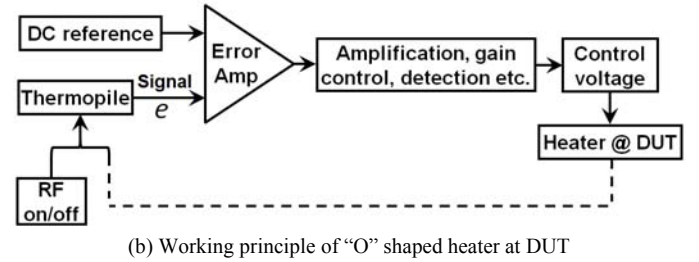
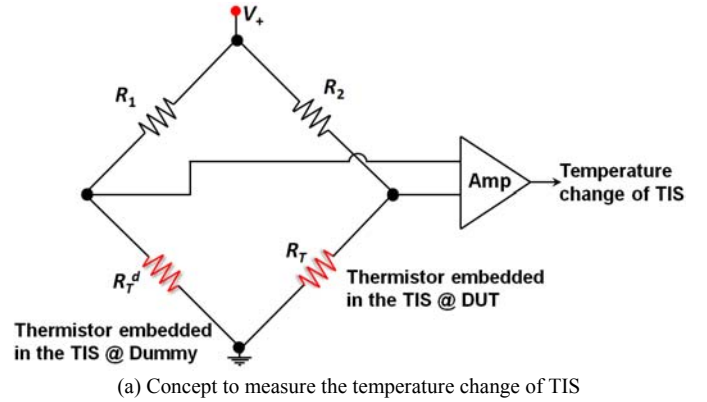


Fig. 2. Operation of additional “O” shaped heater attached to each interface plate and two thermistors embedded in the TISs.

In the improved design, the embedded thermistors are used to measure the temperature change of the TISs as illustrated in Fig.2(a). The “O” shaped heater at DUT is controlled by a feedback loop which is used to substitute the RF power dissipated at the interface and TIS and the loss inside the mount, in the form of control voltage change in the heater at DUT as shown in Fig.2(b). The purpose of the proposed heating is to keep the thermopile signal of the microcalorimeter constant.

As shown in Fig.2(b), the difference between the thermopile signal and the DC reference is used as the input in the feedback loop, and the bias power is set to about 1 mW at DUT side. It is noted that the “O” shaped heater is biased to a temperature higher than the ambient temperature. When RF

power is on, the temperature increases, and therefore the thermopile output voltage varies. The variation of difference between the thermopile signal and the DC reference causes the control voltage of the heater at DUT side to change correspondingly. When the system reaches equilibrium, the thermopile signal should return to its original value.

Therefore, besides the thermistor mount's conventional DC substitution (named as the Main Substitution [MS] in this study), Auxiliary Substitution (AS) is devoted to the process where control voltage of the heater at the DUT side is used to substitute the dissipated RF power on the wall of mount and the TIS etc. In the following, the theoretical background of the proposed design with auxiliary substitution will be discussed.

### B. Theoretical Background and Mathematical Model

The effective efficiency  $\eta_e$  of a mount is defined as the ratio of the DC substitution power  $P_{sub}$  and the RF power  $P_{rf}$  which is absorbed by the mount:

$$\eta_e = \frac{P_{sub}}{P_{rf}}. \quad (4)$$

Here, the total microwave power  $P_{rf}$  dissipated within the mount equals the DC substituted power  $P_{sub}$  and the total loss  $P_{dw}$  (including the loss on the wall of mount and anywhere in the mount). That is

$$P_{rf} = P_{sub} + P_{dw}. \quad (5)$$

It is assumed that all the power is converted to heat which results in the temperature rise of the mount and the TIS (measured by the thermopile and another thermistor attached to the TIS). The AS power  $P_A$  comes from two parts, one part comes from the thermistor mount  $P_{dw}$  and the other part comes from the TIS  $P_i$ . Their contribution factors to the AS are  $k_w$  and  $k_i$  respectively. The proposed relationship is shown as:

$$P_A = P_{off,A} - P_{on,A} = k_w P_{dw} + k_i P_i \quad (6)$$

where  $P_{on,A}$  and  $P_{off,A}$  are the AS power when the RF source is on and off respectively. For the proposed microcalorimeter shown in Fig.1, the measurement procedures are divided into two main steps: the foil short measurement and the calibration measurement.

1) *Foil Short Measurements*: The foil short measurements in the improved design are used to get the relationship between the TIS's temperature change and the AS power while no RF power input to the DC-biased DUT (the mount). A foil short with high reflection is used. The foil short is inserted between the mount and the interface. The AS power and the TIS's temperature at the equilibrium are measured using a digital voltage meter (DVM) when the RF source is on and off correspondingly.

When the power level of RF source varies (i.e., On/Off) during foil short measurements, the TIS's temperature change  $\Delta T_{FS}$  is equal to:

$$\Delta T_{FS} = T_{on,FS} - T_{off,FS} = t_i P_{i,FS} \quad (7)$$

where  $P_{i,FS}$  is the dissipated RF power within the TIS, and  $t_i$  is the proportional coefficient.  $T_{on,FS}$  and  $T_{off,FS}$  are the TIS's temperatures when the RF source is on and off. It is noted that the foil short is closely attached to the interface with a constant temperature which is controlled by the "O" shaped heater during the measurements. Therefore although there is power loss  $P_{FS}$  at the foil short when RF is on, the temperature of the foil short is almost unchanged and same as the temperature of interface. That is,  $\Delta T_{FS}$  has negligible effect from  $P_{FS}$ .

When RF source is on and off, the corresponding control voltage of the heater at the DUT side  $V_{Aon,FS}$  and  $V_{Aoff,FS}$  at thermal equilibrium can be obtained. The AS power  $P_{A,FS}$  in foil short measurements approaches:

$$P_{A,FS} = (V_{Aoff,FS}^2 - V_{Aon,FS}^2) / R_A \quad (8)$$

where  $R_A$  is the resistance of the heater. It is noted that  $P_{A,FS}$  substitutes the RF power  $P_{i,FS}$  dissipated at the TIS and power loss  $P_{FS}$  at the foil short. The following relationship is therefore achieved,

$$P_{A,FS} = k_i P_{i,FS} + k_{FS} P_{FS} \quad (9)$$

where  $k_{FS}$  is the contribution factor of the foil short, and approaches 1.

From (7) and (9), the following relationship can be obtained as,

$$k_i / t_i = (P_{A,FS} - k_{FS} P_{FS}) / \Delta T_{FS}. \quad (10)$$

2) *Calibration Measurements*: The measurements are performed with the foil short removed, and with the RF power input into the thermistor mount directly. This is used to get the AS power and the TIS's temperature change while the DUT consumes the input RF power. The subscript *CAL* is used to indicate the AS power and the corresponding TIS temperature measurements, and *on* and *off* means the status of the RF power is on and off.

The DC substitution power  $P_{sub}$  of DUT can be calculated as follows,

$$P_{sub} = (V_{off,CAL}^2 - V_{on,CAL}^2) / R \quad (11)$$

where  $R$  is the thermistor resistance of the DUT and typically is 200 ohms. It is noted that  $V_{on,CAL}$  and  $V_{off,CAL}$  are  $V_2$  and  $V_1$  as mentioned in (1).

Similar to (9), the AS power  $P_{A,CAL}$  can be estimated as:

$$P_{A,CAL} = k_i P_{i,CAL} + k_w P_{dw} \quad (12)$$

where  $P_{A,CAL}$  comes from the RF powers  $P_{i,CAL}$  and  $P_{dw}$

dissipated at TIS and at the DUT. It is noted that the same factor  $k_i$  is assumed for the contribution of power dissipated at TIS to the AS power for foil short measurements and calibration measurements, although it may vary a little bit due to the slightly different thermal conduction paths.

The AS power  $P_{A,CAL}$  can also be determined through the measurements of the control voltage change in the heater at the DUT side as,

$$P_{A,CAL} = (V_{Aoff,CAL}^2 - V_{Aon,CAL}^2) / R_A. \quad (13)$$

The TIS's temperature change  $\Delta T_{CAL}$  relies on  $P_{i,CAL}$  with a similar relationship as (7),

$$\Delta T_{CAL} = T_{on,CAL} - T_{off,CAL} = t_i P_{i,CAL}. \quad (14)$$

It is noted that similar to  $k_i$ , the same coefficient  $t_i$  is used in the calibration measurements.

From (12) and (14), it can be obtained that:

$$k_i / t_i = (P_{A,CAL} - k_w P_{dw}) / \Delta T_{CAL} \quad (15)$$

Therefore, from (10) and (15), the following relationship can be derived,

$$\frac{\Delta T_{FS}}{\Delta T_{CAL}} = \frac{P_{A,FS} - k_{FS} P_{FS}}{P_{A,CAL} - k_w P_{dw}}. \quad (16)$$

That is,

$$k_w P_{dw} = P_{A,CAL} - \frac{\Delta T_{CAL}}{\Delta T_{FS}} P_{A,FS} + \frac{\Delta T_{CAL}}{\Delta T_{FS}} k_{FS} P_{FS} \quad (17)$$

From (4), (5) and (17), the effective efficiency  $\eta_e$  of the mount can be determined using

$$\eta_e = \frac{P_{sub}}{P_{sub} + \frac{1}{k_w} \left( P_{A,CAL} - \frac{\Delta T_{CAL}}{\Delta T_{FS}} P_{A,FS} + \frac{\Delta T_{CAL}}{\Delta T_{FS}} k_{FS} P_{FS} \right)}. \quad (18)$$

From (18), it can be found that the DUT's effective efficiency mainly depends on the main DC substitution  $P_{sub}$ , the AS powers  $P_{A,FS}$  and  $P_{A,CAL}$ , the TIS's temperature change  $\Delta T_{FS}$  and  $\Delta T_{CAL}$ , and the dissipated RF power  $P_{FS}$  in the foil short which can be determined from theoretical calculation. The only S-parameter measurement in the improved design is for the foil short used. From our experience, the foil short is a piece of flat copper and its reflection coefficient (S-parameter,  $S_{11}$ ) is about 0.9995 from 33 to 75 GHz and therefore  $k_{FS} \approx 1$ .

Moreover, theoretical analysis shows that with the same RF input power, the dissipated power in TIS during the foil short measurements is almost twice that in calibration

measurements. This relationship/difference has been indicated by the ratio of TIS's temperature change,  $\Delta T_{CAL} / \Delta T_{FS}$  in the improved design and proposed evaluation model (18). Practical experience shows that  $\Delta T_{CAL} / \Delta T_{FS}$  approximates to be 0.5.

The contribution factor  $k_w$  is determined indirectly by changing the thermistor mount balance power from  $P_{dc1}$  to  $P_{dc2}$  (with a small change), and through the measurement of the AS power  $P_{A,DC}$  as

$$P_{A,DC} = k_{dc} (P_{dc1} - P_{dc2}). \quad (19)$$

Although there are different thermal conduction paths for DC power  $P_{dc}$  on the thermistor bead and  $P_{dw}$  on the wall and other parts inside the DUT, the thermopile responses is almost the same when  $P_{dc}$  and  $P_{dw}$  are very small. Therefore  $k_w \approx k_{dc}$  which indicates the response of thermopile in the AS measurement.

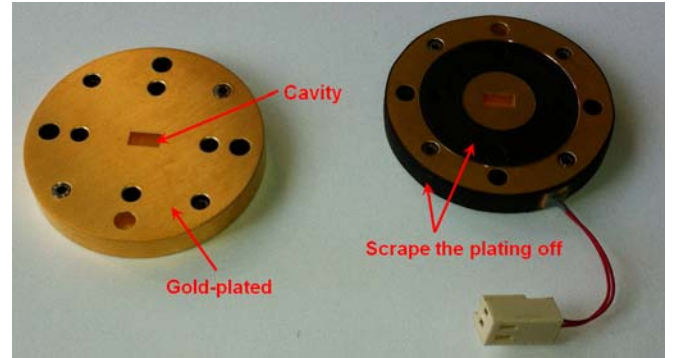


Fig. 3. Picture of the WR-22 thermal isolation waveguide section (TIS), normal TIS (left), modified TIS (right).

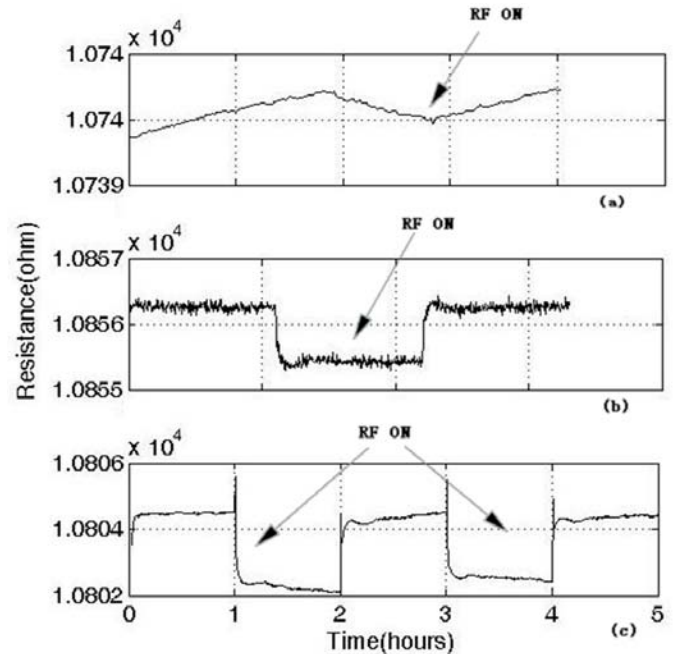


Fig. 4. (a) Normal TIS, (b) Modified TIS without heat preservation, (c) modified TIS with heat preservation.

### III. DESIGN OF THERMAL ISOLATION WAVEGUIDE SECTION

From theoretical analysis in Section II, it can be found that the key part of the improved microcalorimeter is the TIS. The TIS needs to be designed with an excellent thermal isolation ability. Moreover, it must provide a high enough temperature signal and good signal-to-noise ratio (SNR).

Several experimental methods have been studied to improve the temperature rise when RF is on. It is found that, the temperature sensor (thermistor) must be as close as possible to the cavity of TIS as shown in Fig. 3. Fig. 3 shows a final version of modified TIS together with original TIS. The gold-plated layer on the side has been scraped off, and two circular scraped rings have been formed at the top and bottom of TIS to prevent the heat conduction. With the modification, significant improvement has been observed as shown in Fig.4 (a) and Fig.4(b).

However as observed from Fig.4(b), the desired signal is noisy. The investigation found that the noise source was from the wind of the air conditioner in the laboratory. Some actions have been taken to eliminate its influence, by taking the heat preservation to the leads of thermistor and the waveguides outside the microcalorimeter. The wind influence from air conditioner is then reduced significantly.

It is also observed from Fig.4 that the thermal resistance of the modified TIS has been increased which has the effect of increasing the temperature signal of the attached thermistor fifty times compared to the previous TIS (from 0.0001°C to 0.005°C). After thermal insulation/heat preservation of the leads and waveguides of the microcalorimeter, its output SNR was improved around 20 dB. Together with using a low noise amplifier, the TIS's performance could then be further improved as shown in Fig.4(c).

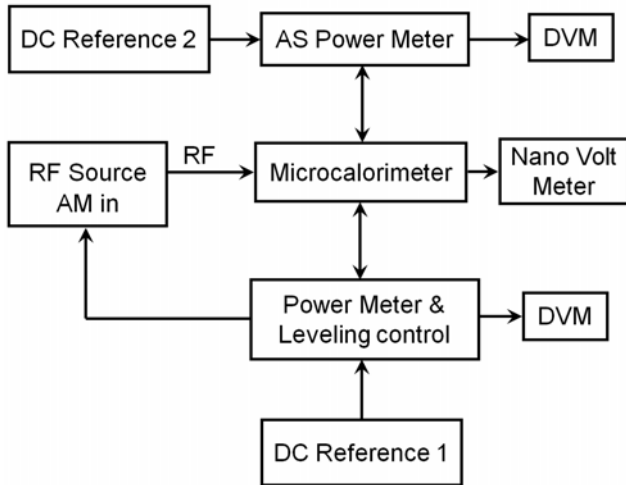


Fig. 5. Measurement system.

## IV. MEASUREMENTS, EVALUATION AND DISCUSSIONS

### A. Measurement System

The whole measurement and calibration system includes a microcalorimeter, an RF source, a main substitution power meter & leveling control, an AS power meter, two DC

references, a Nano Volt Meter and two DVMs as shown in Fig.5. The leveling control is realized by the feedback of the difference between the power meter reading voltage and the reference voltage into AM in of the RF source.

The AS power meter biases the heater at about 1 mW, and takes the amplified thermopile output as a feedback and uses the automatic balance bridge to control the thermopile constant during the measurements. The nanometer is used for the TIS's thermistor measurements. The measurements are automatically controlled by a software program.

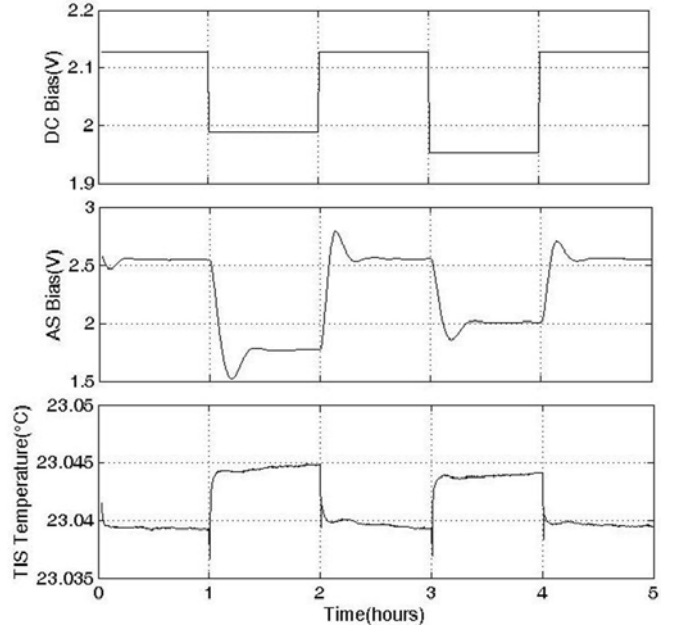


Fig. 6. Example of raw data taken with the WR-22 microcalorimeter. Top: DC bias power for the DUT. Middle: Auxiliary Substitution (AS) power. Bottom: TIS temperature.

### B. Measurement Results

Examples of the calibration results using the WR-22 microcalorimeter are shown in Fig. 6 and Fig. 7. The status of the RF source was changed at an interval of 1 hour. The corresponding variations of the MS power (DC substitution of the DUT), the AS power, and the resulting temperature change are shown in Fig. 6, where the temperature is derived from the thermistor's resistance following the relationship [12],

$$T_1 = \frac{1}{\frac{1}{B} \ln\left(\frac{R_{T1}}{R_{T2}}\right) + \frac{1}{T_2}} \quad (20)$$

where  $B$  is a characteristic of the thermistor material,  $R_{T2}$  is the thermistor's resistance at a known temperature  $T_2$ , and  $R_{T1}$  is the thermistor's resistance at a temperature  $T_1$  in Kelvin. Detailed information regarding eq. (20) can be obtained from [12]. Using the proposed calibration model in (18), the effective efficiency of the mount is then determined and shown in Fig.7.



### C. Discussion of the Uncertainty

From (18), it can be found that the uncertainty sources in the proposed design include the DC power measurements, the temperature measurements and the short loss evaluation. As the DC power measurement has a very small uncertainty (< 0.01%), the main uncertainty sources are the temperature change measurements during the calibrations and the foil short measurements. For example, the uncertainty contribution from the temperature change can be evaluated using (21) and (22), the measurement uncertainty from these two items is less than 0.1%. The temperature value can be measured very accurately to be about  $10^{-6}$  °C. However, the SNR of the temperature signal is found to be an important factor affecting uncertainty evaluation and is about 1% using the average estimation.

$$|u_{\eta_e, \Delta T_{CAL}}| = \left| \frac{\eta_e}{P_{sub}} \frac{1}{k_w} \left( \frac{P_{A,FS}}{\Delta T_{FS}} + \frac{k_{FS} P_{FS}}{\Delta T_{FS}} \right) u_{\Delta T_{CAL}} \right| \quad (21)$$

$$|u_{\eta_e, \Delta T_{FS}}| = \left| \frac{\eta_e}{P_{sub}} \frac{1}{k_w} \left( \frac{\Delta T_{CAL} P_{A,FS}}{\Delta T_{FS}^2} + \frac{\Delta T_{CAL} k_{FS} P_{FS}}{\Delta T_{FS}^2} \right) u_{\Delta T_{FS}} \right| \quad (22)$$

Typical measurement uncertainties associated with the improved design using the proposed evaluation method are also shown in Fig.7 as a reference. The performance of the improved design has been assessed through a recently completed CCEM key comparison [13] where a detailed evaluation of the measurement uncertainties at the NIM, China can be referred.

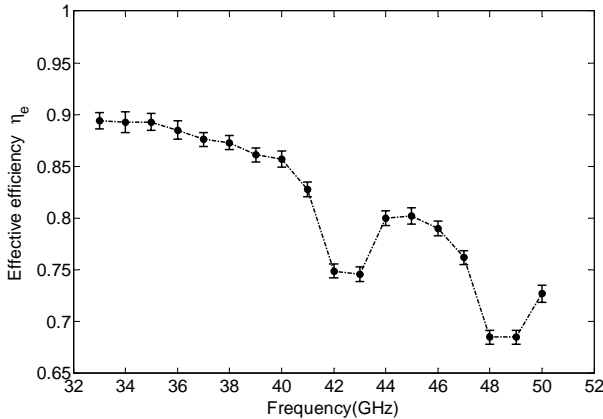


Fig. 7. Example of DUT's effective efficiency with the WR-22 microcalorimeter. Uncertainty bars are shown for  $k = 2$ .

### V. CONCLUSION

In this paper, an improved design and simplified evaluation technique for a waveguide microcalorimeter were reported. Based on the traditional twin-line microcalorimeter design at NIST, another thermistor is added to measure the TIS's temperature change in the proposed design. Through the theoretical analysis, it is found that, generally this technique can simplify the measurement procedure and reduce the S-

parameter measurements for microcalorimeter assemblies.

From the investigations, it is found that the output SNR of the TIS is an important issue. The SNR has been improved by enhancing the temperature stability of microcalorimeter. From the analysis, this approach could be applied to any waveguide microcalorimeter. The capability of the improved design and proposed evaluation technique has been assessed through a recent CCEM key comparison with good agreement.

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