A Self-Calibrated Transfer Standard for Microwave Calorimetry

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***Abstract*—We developed a new calibration technique for measuring the correction factor of a calorimeter with a vector network analyzer. Based on a wave-parameter formulation, we developed analytic formulas for the correction-factor (g) and effective-efficiency (η). This allows us to calibrate both the calorimeter and the thermistor mount in a single step. This greatly reduces the number of physical parameters involved in calibration processes while tracking correlated uncertainty.**

***Index Terms*—Correction factor, microcalorimeter, microwave power, transfer standard, vector wave parameter.**

I. Introduction

Power is one of the fundamental parameters in microwave metrology. A number of other microwave parameters are derived from precision measurements of either relative or absolute power. A thermistor mount serves as a popular metrology-grade tool and is recognized as a transfer standard for microwave power measurements. A thermistor mount is characterized by its effective efficiency that accounts for the difference between the DC substituted power and the microwave power delivered to it.

Calibrations of the thermistor-mount effective efficiency are often conducted in a calorimeter to achieve high precision. A thermal isolation section is integrated in the calorimeter to stabilize the thermal process for efficient measurements. A considerable amount of research has focused on determining the correction factor (g-factor) of calorimeters, which removes the loss contribution of the thermal isolation section to the power measurement while the calibration of a thermistor mount is undertaken. In this study, we present a new measurement technique using wave parameters to find the g-factor of calorimeters with a self-calibrated thermistor mount.

II. Calorimeter G-Factor

The g-factor is characterized by monitoring the thermopile voltage rise associated with the power dissipation in the thermal isolation section. There have been various methods developed for g-factor measurements, such as the line method, the thru method, and the short and offset-short method [1]. Regardless of what method we choose, the incident power (P_{inc}) at the reference plane of interest is almost always needed for g-factor measurements.

In order to obtain P_{inc}, a three-port coupler is often inserted between the calorimeter and the signal generator in the traditional experimental setup. The side arm of the coupler is terminated by a power sensor, usually a thermistor mount, and P_{inc} can be inferred from its reading. There are complications associated with this approach; 1) the equivalent source mismatch and the coupling coefficient of the coupler need to be measured separately, and 2) it requires a calibrated power sensor with known effective efficiency. Although complication 1 can be overcome with lengthy scattering (S-) parameter measurements, calibrated power sensors may not be available to begin with. In the following section, we show how to measure the g-factor without the need of calibrated sensors and couplers.

III. Theoretical Framework of New Technique

Since a vector network analyzer (VNA) consists of bi-directional couplers in its test ports, the use of a VNA to replace the combination of the signal generator, the coupler, and the power sensor is natural. Calibrated wave parameters can be obtained after calibrations to deduce P_{inc} needed for g-factor measurements. We formulate the short method in this report. Other methods can be handled in a similar manner.

A. Intrinsic G-Factor

We first introduce a reduced form of the g-factor and call it the intrinsic g-factor (g_c). For the foil-short method, we express this as

$$g_c = \frac{P_{\text{FS}}}{P_{\text{inc}}\left(1+|\mathbf{\Gamma}_{\text{FS}}|^2\right)} - \frac{1-|\mathbf{\Gamma}_{\text{FS}}|^2}{1+|\mathbf{\Gamma}_{\text{FS}}|^2}, \tag{1}$$

where P_{FS} is the measured power dissipation related to the loss of the thermal isolation section and the foil short, P_{inc} is the power incident on the foil short, and $\mathbf{\Gamma}_{\text{FS}}$ is the reflection coefficient of the flush short. The first term in (1) indicates the portion of the power dissipated in the thermal isolation section and the second term represents the part of the loss due to the flush short. The correction given by the second term is necessary due to the fact that only the thermal isolation section will be present in the final effective-efficiency measurement.

B. VNA S-Parameter and Power Calibrations

Prior to the g-factor measurements with the short method, we performed a one-port S-parameter calibration and power calibration at the reference plane behind the thermal isolation section where the foil short will be attached. A measurement diagram with network analysis is shown in Fig. 1.

Three or more calibration artifacts (e.g., short, open, and load) are sequentially connected at the reference plane to

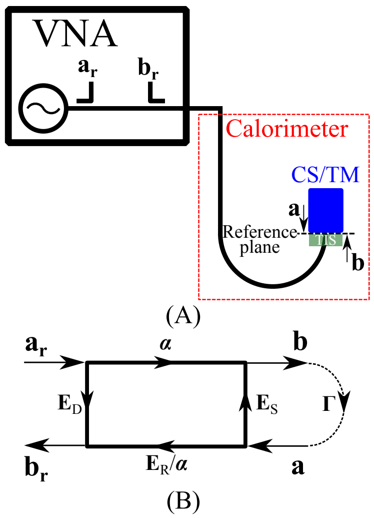

Fig. 1. (A) Illustration of measurement setup. Calibration standards (CS) and a thermistor mount (TM) are sequentially connected at the reference plane to perform the calibration. (B) Equivalent network for error-term analysis.

determine error coefficients $\mathbf{E}_{\text{D}}$, $\mathbf{E}_{\text{S}}$, and $\mathbf{E}_{\text{R}}$ of Fig. 1B. This would be adequate if we were only interested in measuring the reflection coefficient of a device under test (DUT) attached to the reference plane after the calibration. However, to know the incident power on the DUT, the knowledge of $\boldsymbol{\alpha}$ (or more precisely its magnitude $|\boldsymbol{\alpha}|$) is required.

We now connect a thermistor mount with unknown η to the reference plane and record the VNA raw readings $\mathbf{a}_{\text{r}}^{\text{TM}}$ and $\mathbf{b}_{\text{r}}^{\text{TM}}$. In wave-parameter representation, the power delivered to the thermistor mount is simply $|\mathbf{b}^{\text{TM}}|^2 - |\mathbf{a}^{\text{TM}}|^2$. The deliverable power can also be calculated from the DC substituted power scaled by the effective efficiency as

$$P = \frac{V_{\text{off}}^2 - V_{\text{on}}^2}{\eta R_0}, \tag{2}$$

where V_{on} and V_{off} represent the RF on-and off-voltage, respectively and R_0 is the thermistor mount resistance. As a result, the modulus of $\boldsymbol{\alpha}$ can be determined as follows:

$$|\boldsymbol{\alpha}| = \sqrt{\frac{V_{\text{off}}^2 - V_{\text{on}}^2}{\eta R_0 \left(\begin{array}{c} \left| \frac{\mathbf{E}_{\text{R}} - \mathbf{E}_{\text{S}}\mathbf{E}_{\text{D}}}{\mathbf{E}_{\text{R}}} \mathbf{a}_{\text{r}}^{\text{TM}} + \frac{\mathbf{E}_{\text{S}}}{\mathbf{E}_{\text{R}}} \mathbf{b}_{\text{r}}^{\text{TM}} \right|^2 \\ - \left| -\frac{\mathbf{E}_{\text{D}}}{\mathbf{E}_{\text{R}}} \mathbf{a}_{\text{r}}^{\text{TM}} + \frac{1}{\mathbf{E}_{\text{R}}} \mathbf{b}_{\text{r}}^{\text{TM}} \right|^2 \end{array} \right)}}. \tag{3}$$

Note that η is required to complete the power calibration. To this end, we define scaled wave quantities $\hat{\mathbf{a}}$ and $\hat{\mathbf{b}}$. So that their magnitude can be resolved directly without knowing η,

$$\begin{bmatrix} \hat{\mathbf{a}} \\ \hat{\mathbf{b}} \end{bmatrix} = \sqrt{\eta} \begin{bmatrix} \mathbf{a} \\ \mathbf{b} \end{bmatrix} = \frac{\sqrt{\eta}\boldsymbol{\alpha}}{\mathbf{E}_{\text{R}}} \begin{bmatrix} -\mathbf{E}_{\text{D}} & 1 \\ \mathbf{E}_{\text{R}} - \mathbf{E}_{\text{S}}\mathbf{E}_{\text{D}} & \mathbf{E}_{\text{S}} \end{bmatrix} \begin{bmatrix} \mathbf{a}_{\text{r}} \\ \mathbf{b}_{\text{r}} \end{bmatrix}. \tag{4}$$

In essence, the true wave quantities $\mathbf{a}$ and $\mathbf{b}$ differ merely by a factor of $\sqrt{\eta}$ from $\hat{\mathbf{a}}$ and $\hat{\mathbf{b}}$. This manipulation enables us to reach a closed form of η evaluation in what follows.

C. Foil-Short Measurement

We now insert a copper foil as a flush short at the reference plane between the thermistor mount and the thermal isolation section and drive the calorimeter with the VNA set at the frequency of interest. The thermistor mount is biased by the power meter at the nominal DC voltage value. Aside from P_{FS} calculated from the thermopile voltage, all other variables in (1) can be computed from raw readings of wave quantities with completely solved error coefficients ($\mathbf{E}$'s) and partially solved $|\boldsymbol{\alpha}|$. They are expressed as

$$P_{\text{FS}} = e_{\text{FS}}/k_{\text{FS}} - e_{\text{DC}}/k_{\text{DC}}, \tag{5a}$$

$$\boldsymbol{\Gamma}_{\text{FS}} = \mathbf{a}^{\text{FS}}/\mathbf{b}^{\text{FS}} = \hat{\mathbf{a}}^{\text{FS}}/\hat{\mathbf{b}}^{\text{FS}}, \tag{5b}$$

$$P_{\text{inc}} = \left|\mathbf{b}^{\text{FS}}\right|^2 = \left|\hat{\mathbf{b}}^{\text{FS}}\right|^2/\eta. \tag{5c}$$

Here, e_{FS} and e_{DC} are stabilized thermopile voltages while the VNA is turned on and off respectively, and k_{FS} and k_{DC} are the proportionality factors of the thermopile. We now have explicitly acquired g_c as a function of η after substitution of (5)'s for variables in (1).

D. Effective-Efficiency Measurement

Next, we move on to the measurement of effective efficiency using a signal source with the standard approach. η is related to g_c as follows

$$\eta = \left(1 + g_c \frac{1 + |\boldsymbol{\Gamma}_{\text{TM}}|^2}{1 - |\boldsymbol{\Gamma}_{\text{TM}}|^2}\right) \frac{1 - \left(\frac{V_2}{V_1}\right)^2}{\frac{e_2/k_2}{e_1/k_1} - \left(\frac{V_2}{V_1}\right)^2}. \tag{6}$$

Thermal processes arrive at equilibrium while the signal source is off and then turned on. Under these two conditions, the power meter reads V_1 and V_2, the thermopile reaches e_1 and e_2, and its proportionality factors are k_1 and k_2. $\boldsymbol{\Gamma}_{\text{TM}}$ is the reflection coefficient of the thermistor mount. The term in the parenthesis corresponds to the conventional g-factor, differing from g_c by mismatch corrections of the thermistor mount.

The expansion of g_c in terms of η in (6) yields η in closed form as shown in (7), which completes the self calibration of the thermistor mount:

$$\eta = \frac{1 - \frac{1+\left|\hat{\mathbf{a}}^{\text{TM}}/\hat{\mathbf{b}}^{\text{TM}}\right|^2}{1-\left|\hat{\mathbf{a}}^{\text{TM}}/\hat{\mathbf{b}}^{\text{TM}}\right|^2} \cdot \frac{1-\left|\hat{\mathbf{a}}^{\text{FS}}/\hat{\mathbf{b}}^{\text{FS}}\right|^2}{1+\left|\hat{\mathbf{a}}^{\text{FS}}/\hat{\mathbf{b}}^{\text{FS}}\right|^2}}{\frac{\frac{e_2/k_2}{e_1/k_1} - \left(\frac{V_2}{V_1}\right)^2}{1-\left(\frac{V_2}{V_1}\right)^2} - \frac{1+\left|\hat{\mathbf{a}}^{\text{TM}}/\hat{\mathbf{b}}^{\text{TM}}\right|^2}{1-\left|\hat{\mathbf{a}}^{\text{TM}}/\hat{\mathbf{b}}^{\text{TM}}\right|^2} \cdot \frac{\frac{e_{\text{FS}}}{k_{\text{FS}}} - \frac{e_{\text{DC}}}{k_{\text{DC}}}}{\left(\left|\hat{\mathbf{a}}^{\text{FS}}\right|^2 + \left|\hat{\mathbf{b}}^{\text{FS}}\right|^2\right)}}. \tag{7}$$

With the η value at our disposal, we can accurately determine P_{inc} in (5c) and that in turn provides the g_c value in (1).

IV. Conclusion

We demonstrated a new method of measuring the effective efficiency of a thermistor mount in an uncalibrated calorimeter. By use of a partially calibrated VNA for g-factor measurements, both η and g_c can be acquired in closed form in terms of wave parameters and voltages. Experimental validation with correlated uncertainty will be reported at the conference.

References

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