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Improvements on INRIM Coaxial Microcalorimeter and Outcome of a Model Comparison

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***Abstract*— This paper describes hardware and software improvements of the Istituto Nazionale di Ricerca Metrologica (INRIM) coaxial microcalorimeter together with their outcome on the primary power standard realization in the frequency band 0.05–40 GHz. A better temperature and power stabilization turned out to provide an improved signal/noise ratio and a drift reduction in every working condition of the microcalorimeter. The INRIM correction model is also compared with a traditional, but faster, one in terms of measurement uncertainty. The outcomes are presented in form of a 2.92-mm thermoelectric power sensor calibration together with the results that show an improved stability and repeatability of the measurement system.**

***Index Terms*— Broadband microcalorimeter, microwave measurements, microwave standards, power measurement, thermoelectric devices.**

I. INTRODUCTION

IN THE radio frequency and microwave range, a key quantity always well defined and measurable is the electromagnetic power [1]. Therefore, the power standard is of the utmost importance for primary electromagnetic metrology. All national metrology institutes (NMIs) realize the high-frequency (HF) primary power standard, tracing the calibration of a thermal detector to the *dc power standard*. The *principle of equivalence of the thermal effects* is applied for that purpose. This technique has been introduced in the late 1950s, and today, it is usually referenced as microcalorimeter technique [1]–[3]. Up to now, alternatives do not exist yet, and therefore, the continuous improvement of microcalorimeter systems in terms of both hardware and software is very important for all NMIs. Even though microcalorimeters exist both in waveguide and in coaxial line with different performances [4]–[13], Istituto Nazionale di Ricerca Metrologica (INRIM) mainly developed coaxial systems because of their broadband characteristics. Furthermore, it has been one of the first NMIs to propose the microcalorimeter based on the thermoelectric detection as an alternative to the more classical bolometric detection [14]–[24]. Sensors based on thermoelectric principle are less sensitive to ambient temperature variations, and are not downward-frequency limited.

The improvements to INRIM measurement system reached recently a new level by refining temperature and power controls. This paper shows the effects of these improvements on the calibration of a coaxial thermoelectric power sensor in the frequency band 0.05–40 GHz, as already anticipated in [25].

II. SYSTEM DETAILS

The INRIM microcalorimeter is an adiabatic dry microcalorimeter fitted with a 2.92-mm twin coaxial-line inset. The system architecture is slightly different from that of the model cited in the literature of the same authors. It has been specifically designed to calibrate thermoelectric power sensors in terms of effective efficiency in the frequency range 0.01–40 GHz. The temperature stabilization of the microcalorimeter load is obtained by means of a combination of passive and active metal shields separated by a polymeric foam as an insulating material. The temperature control system is based on Peltier elements and a wire heater driven by PID controllers. It requires to be operated inside a preconditioned room at the temperature of (23.0 ± 0.3) °C and relative humidity of (50 ± 5)%.

Former systems [14]–[24], placed inside the same preconditioned room, were able to maintain the measurement chamber at (25.00 ± 0.01) °C for about 50 min. In the new design, the thermal stability has been increased of about one order of magnitude (about 3 mK) for a longer duration (more than 20 h). This allows better measurement uncertainties when the microcalorimeter operates in critical conditions, that is, when the sensor losses are very low.

However, sensitivity and accuracy of the INRIM coaxial microcalorimeter have been improved not only with respect to its thermal control system, but also to the stabilization of the measurement power level.

To be more specific on the new design and with reference to Fig. 1, we modified the insulating sections, and furthermore, an external one (I IS) has been added to the thermostat to improve the thermal insulation of the microcalorimeter load against the external environment. Second, an additional passive planar shield (IV SHIELD) has been placed in front of the measurement port to reduce the thermal offset between reference and measurement channel even without power injection. Finally, a sensitive temperature control has been applied to the massive aluminum cylinder (III SHIELD) that embraces the measurement chamber.

The advantages of this hardware improvement on the temperature stability can be seen in Fig. 2 that shows the temperature behavior in the microcalorimeter at the level of

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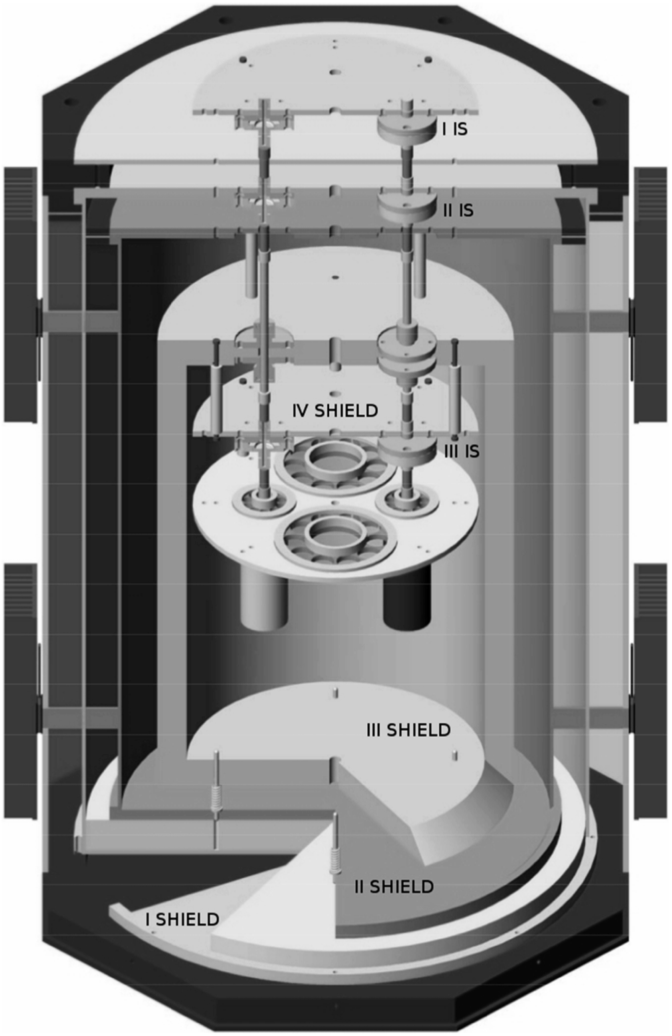

Fig. 1. Computer-Aided Design (CAD) picture showing the latest INRIM microcalorimeter that consists of the basic structure of the thermostat together with the inset elements.

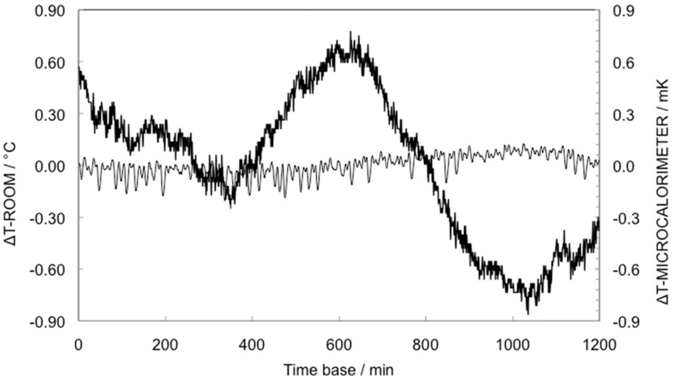

Fig. 2. Temperature variations outside and inside microcalorimeter, during a typical measurement cycle. Left y-axis reports the ambient temperature variations (thin line). Right y-axis shows the temperature fluctuations inside microcalorimeter (bold line).

the thermopile fixture during the substitution of the reference power (REF) level (1 mW at 1 kHz) with an equivalent HF power. The plot shows clearly that the temperature fluctuations inside the microcalorimeter are always below 1 mK, three orders lower than the fluctuation of the environment.

Furthermore, a good thermal decoupling is confirmed by the calculated correlation coefficient between the external temperature variations and the thermopile output that results in 0.016. This coefficient has been evaluated by means of repeated measurements of both the temperature and the asymptotic value of the thermopile voltage and according to [26] and [27].

Another improvement concerns the power output stabilization of the generators used to perform the REF–HF–REF power substitution into the system. This has been obtained by adding an algorithm based on PID controllers and $\Sigma\Delta$-modulators to the measurement software. The improvement has a direct effect on the repeatability of the measurements.

III. MICROCALORIMETER MATHEMATICAL MODEL

The new coaxial microcalorimeter measures the *effective efficiency* η_{e} of a thermoelectric sensor mount, which is defined as the ratio of the measured power P_{M}, that is, the HF power actually converted into a dc output by the sensor, to the total absorbed power $P_{\mathrm{A}} = (P_{\mathrm{M}} + P_{\mathrm{X}})$

$$\eta_{\mathrm{e}} = \frac{P_{\mathrm{M}}}{P_{\mathrm{M}} + P_{\mathrm{X}}} \tag{1}$$

where P_{X} is the power loss in the sensor mount [15]–[17].

Operatively, the expected value of η_{e} can be obtained through a mathematical model that has been widely described in [15]–[24]

$$\eta_{\mathrm{e}} = \frac{e_2}{e_1 - (1 + |\Gamma_{\mathrm{s}}|^2)\frac{e_{1\mathrm{SC}}}{2}} \tag{2}$$

where e_1 and e_2 are the responses of the electrical thermometer of the microcalorimeter (i.e., a thermopile) to the HF power and to the REF power substituted into the system, respectively. The voltage e_{1SC} corrects the microcalorimeter loss effects that result as dominant error contribution in the whole process of the power standard realization. This voltage is determined by means of the short circuit technique [15], [20], and it has to be halved to take into account the power reflected back by the short circuit. Finally, the term $(1 + |\Gamma_{\mathrm{S}}|^2)$ is an additional correction necessary to enhance the accuracy of the power standard when the reflection coefficient Γ_{S} of the power sensor under calibration is not negligible [18].

We strongly support the use of (2), but since it requires the repetition of the whole measurement procedure twice to calibrate both the sensor and the microcalorimeter in short-circuit condition, it is very time consuming.

Anyway, we will demonstrate, later in this paper, that the traditional method used in the past by INRIM and other NMIs is less accurate. This traditional model can be derived directly from the η_{e} definition (1) by adding the rate δP_{L} of the microcalorimeter feeding line losses that influence η_{e}. It is given by

$$\eta_{\mathrm{e}} = \frac{P_{\mathrm{M}}}{P_{\mathrm{M}} + P_{\mathrm{X}} + \delta P_{\mathrm{L}}} = \frac{\eta_{\mathrm{e}}^{\mathrm{raw}}}{1 - \eta_{\mathrm{e}}^{\mathrm{raw}}\left(\frac{\delta P_{\mathrm{L}}}{P_{\mathrm{M}}}\right)} = \frac{e_2}{e_1 - e_2\left(\frac{\delta P_{\mathrm{L}}}{P_{\mathrm{M}}}\right)} \tag{3}$$

where $\eta_{\mathrm{e}}^{\mathrm{raw}}$ is equal to e_2/e_1 and represents the uncorrected effective efficiency obtained from the measurements.

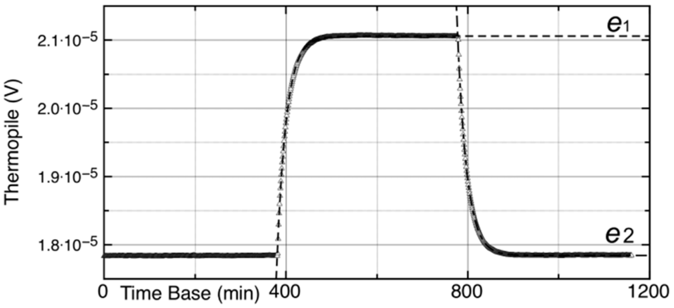

Fig. 3. Thermopile response at 1-mW REF–HF–REF power substitution, together with the fitting results.

From the S-parameter theory, the perturbation term in the denominator of (3) can be expressed as a function of the feeding line transmission parameter S_{12} and the power sensor reflection coefficient Γ_S. Then, under the reasonable hypothesis that only 50% of the feeding line losses influences the measurements [1], we obtain the following:

$$\eta_e = \left(\frac{1 + |S_{12}|^2(1 - 2|\Gamma_S|^2)}{2|S_{12}|^2(1 - |\Gamma_S|^2)} \right) \eta_e^{\text{raw}}. \tag{4}$$

The previous hypothesis about the influence of line losses can be justified considering the thermodynamic model of a line section with uniformly distributed losses. If its ports are at the same temperature, then half of the generated thermal energy leaves the line through each port.

Model (4) avoids running the microcalorimeter in short-circuit condition, but has intrinsic limitations that we will highlight in the next paragraph, where we will show how its performance relates to (2).

IV. MEASUREMENTS AND DATA ANALYSIS

Experimental work consists of the calibration of a thermoelectric power sensor fitted with a 2.92-mm connector so to realize the primary power standard in the frequency band 0.01–40 GHz.

Measurements have been performed at 1-GHz step, but the numerical value of the measurand is hereby given, together with its uncertainty, only at seven specific frequencies (50 MHz, and 1, 10, 18, 26.5, 33, and 40 GHz), known to be critical or limiting for some coaxial connector/line types.

Examples of detailed uncertainty budgets are given to support comments and conclusion. Raw effective efficiency η_e^{raw} has been calculated by means of fitting/averaging processes applied to thermopile outputs e_1 and e_2, as already described in [16]–[24]. In short, we used a fitting method based on the Levenberg–Marquardt algorithm that requires as data input the thermopile voltage and the time base value together with their uncertainties [26]. The algorithm returns the asymptotic value of the thermopile output. Fig. 3 and, its closeup, Fig. 4 show the output of the mentioned calculation process superimposed onto the real thermopile output voltage, for one complete REF–HF–REF substitution cycle at 40 GHz. Applying the mentioned process to several power substitution cycles, we can obtain the expected mean value of the measurand with an associated standard deviation (σ).

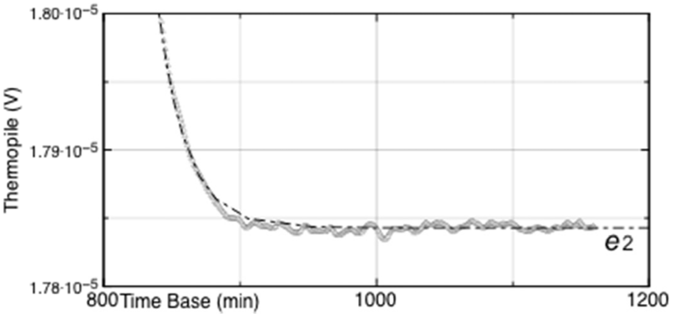

Fig. 4. Expansion of the thermopile response at 1-mW HF–REF substitution step to better highlight the quality of the fitting process.

TABLE I
CALIBRATION LIST OF THE THERMOELECTRIC POWER STANDARD

Freq. (GHz)	η_e^{raw}	$u(\eta_e^{\text{raw}})$ 1σ	η_e Mod. (2)	$u(\eta_e)$ 1σ	η_e Mod. (4)	$u(\eta_e)$ 1σ
0.05	0.9879	0.00045	0.9923	0.00049	0.9926	0.0054
1	0.9662	0.00043	0.9806	0.00048	0.9804	0.0057
10	0.9097	0.00038	0.9383	0.00044	0.9371	0.0128
18	0.8855	0.00037	0.9270	0.00043	0.9281	0.0128
26.5	0.8725	0.00036	0.9154	0.00043	0.9118	0.0356
33	0.8633	0.00035	0.9035	0.00043	0.9031	0.0373
40	0.8473	0.00034	0.8974	0.00043	0.8980	0.0307

TABLE II
DETAILS OF UNCERTAINTY BUDGET AT 40 GHz FOR THERMOELECTRIC STANDARDS (EXCLUDING ADIMENSIONAL REFLECTION AND TRANSMISSION COEFFICIENTS, QUANTITIES AND RELATED UNCERTAINTIES ARE IN VOLTS)

Influence Variable	Measured Value y	Measurement Uncertainty $u(y)$	Sensitivity coefficient $\|c(y)\|$	Uncertainty Contribution $c(y)u(y)$
Correction model (2)				
e_1	2.1058E-05	7.0E-09	4.5138E+04	0.00031
e_2	1.7843E-05	4.0E-09	5.0297E+04	0.00020
e_{1SC}	2.3273E-06	7.3E-09	2.2800E+04	0.00016
Γ_S	0.1013	0.0130	0.0106	0.00013
$u(\eta_e)$				0.00043
Correction model (4)				
e_1	2.1058E-05	7.0E-09	4.5138E+04	0.00031
e_2	1.7843E-05	4.0E-09	5.0297E+04	0.00020
S_{12}	0.6992	0.0122	2.5084	0.03058
Γ_S	0.1013	0.0130	0.1874	0.00243
$u(\eta_e)$				0.03068

The correction terms appearing in (2) and (4) are calculated by means of the software mentioned before, when it is the case (e_{1SC}) and through independent measurements of reflection coefficient Γ_S and transmission parameter S_{12}.

Table I shows the raw effective efficiency and the values of the same measurand corrected according to both (2) and (4), together with their uncertainty terms, at the specific frequencies. The total measurement uncertainty of the measurand η_e has been calculated by applying the Gaussian error propagation on (2) and (4), and considering the possible existence of correlation among the influence quantities as suggested in [27].

Table II shows the detailed uncertainty budgets related to (2) and (4) at 40 GHz. Correlation terms exist only for the voltages e_1 and e_2, but they are not reported in Tables I and II because their contribution to the uncertainty turned out to be negligible if compared with other uncertainty contributions. No correlation exists among the quantities $e_{1\mathrm{SC}}$, Γ_S, S_{12}, e_1, and e_2, because they are either measured with different independent methods or at different times and conditions.

At first glance, the results of Table I show a good agreement between the expected values of effective efficiency obtained using (2) and (4), even though at all frequencies, (4) results in bigger uncertainties. This behavior was, however, expected, because there are difficulties in determining the actual values of both the transmission parameter S_{12} and the HF power loss rate *on site*, without dismounting the line inset. We considered that only 50% of the losses of the last insulating section (III IS) affects the load, as described in Section III. This hypothesis revealed to be reasonable, but evidently not enough valid to obtain the best expected value of η_e with the best uncertainty.

The mentioned assumptions are not requested if we introduce the correction based on the method that uses the short circuit condition (2). Indeed, in this case, the voltage $e_{1\mathrm{SC}}$ automatically account for the loss rate of the feeding line, whatever long and complex it is. Of course, this turns out to be a benefit for the total measurement accuracy.

Looking at Table II, we see that the most limiting factor in the accuracy budget is the term S_{12}. At present, it is very difficult to find the actual values of the feeding line losses *on site*. This condition implies to be very conservative with both its value and uncertainty. Furthermore, and unfortunately, the sensitivity coefficient $c(S_{12})$ derived from the mathematical model (4) is quite high; this made the uncertainty contribution worse.

V. CONCLUSION

After having introduced thermodynamic improvements to the INRIM coaxial microcalorimeter, we performed a full calibration of a thermoelectric power sensor in the frequency band 0.01–40 GHz using two different correction models. The outcome of this particular comparison confirms that the actual INRIM microcalorimeter exhibits superior accuracy when it is calibrated by means of the short-circuit technique. The correction technique based on the measurement of scattering parameters by means of network analyzer allows to save time, but gives as results a measurement accuracy significantly lower, at least for the INRIM system. In any case, it indirectly confirms the validity of (2) that is the official correction currently applied to the coaxial microcalorimeter measurement at INRIM.

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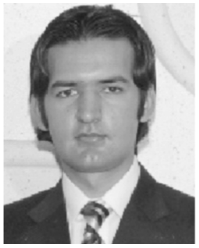

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