RECENT EVOLUTIONS OF THE MICROCALORIMETER TECHNIQUE

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ABSTRACT

The microcalorimeter technique continues to be the key technique for the realization of the primary power standards in the high frequency, because at the state of the art, only it allows tracing the power standards to the direct current standard, that is a SI quantity. This traceability is obtained through the determination of the effective efficiency, usually indicated by η_e, of a power sensor as a frequency function. Even though since long time the microcalorimeter is a highly explored measurement system, the first realizations being dated from the late of 1950s, still it is possible to propose improvements that should finally increase its accuracy. Actually this one ranges realistically from 0.2% to 2%, if a significant frequency band is considered, e.g. from the radio frequencies to the millimeter waves. Better values are obtainable below 1 GHz, but beyond 18 GHz a 2% still is a challenge, particularly for power sensors in coaxial line of 3.5 mm, 2.92 mm and 2.4 mm. Waveguide power sensors allow to obtain the mentioned accuracy more easily, but in some frequency bands they are no longer available and coaxial solution could be mandatory. In the paper we highlight the limiting factors of the coaxial microcalorimeter accuracy and how we worked around to improve the technique.

INTRODUCTION

Microcalorimeter was developed for bolometer sensors based on thermistors mainly, because these allow measuring the high frequency (HF) power by means of the *DC power substitution method*. Up to now thermistors have been working well, even if they are downward frequency limited, that is, not usable below 10 MHz or more realistically 50 MHz. However, power sensors based on indirect heating thermocouples have been successfully used as an alternative to the thermistors for realizing the HF power standard up to 26.5 GHz in 3.5 mm coaxial line. The upper frequency limit has been recently extended up to 40 GHz in 2.92 mm coaxial line and in a near future is expected up to 50 GHz by using the 2.4 mm coaxial line. The change in the microcalorimeter technique is more then an option, because thermistors are no more available in waveguide mounts and rumors exist that even the production of the coaxial versions could be suspended by the manufactures in favor of the more commercial thermocouples or diodes. Anyway, the use of the thermocouples in realizing of the HF power standards turned out to be an improvement to the technique, in some sense. Thermocouples are not downward frequency limited; they can accept as reference power both DC power and low frequency (LF) power; this sensor type, that still is a true r.m.s. sensor, is not sensitive to the absolute temperature like thermistors, a particular that make the device more efficient in the power standard transfer. Thermocouples have been used as traveling standards in an international CCEM comparison (CCEM.RF-K10.CL) in which the authors experimented for the first time a new twin-type coaxial microcalorimeter specifically optimized for such sensors. Using thermocouples as transfer standards, the classic microcalorimeter technique requires some small changes and the final result is a more simple calibration process. The limiting factor in the microcalorimeter technique is related to the losses of the insulating line that supply HF or both HF and LF to power sensor under calibration. The advances in the hardware are no more enough efficient because beyond 1 GHz the line losses may not be reduced up to be negligible, even through a more accurate fabrication process of the items. The right way is therefore that to determine the losses or mainly the effect they have on the measurand. In other words it is necessary to determine accurately the efficiency of the microcalorimeter by means of a calibration process. This is everything but not academic, because it requires changes in the hardware configuration of the microcalorimeter, with the possibility to measure irrelevant parameters for the power sensor under calibration.

MICROCALORIMETER

The Microcalorimeter is a relatively simple measurement system adjusted for measuring power ratios rather then absolute power levels [1]. A thermostat insulates a power sensor that realizes the thermal load of the microcalorimeter from the external environment while transmission lines with low thermal conductance supply the power sensor alternatively with HF power and DC or LF reference power levels. This power substitution allows the development of two different states of thermodynamic equilibrium inside the thermostat, while a thermopile detects continuously the temperature variations of the thermal load associated to each state change. Based on the experimentally verified assumption that the thermopile response is linear with the temperature, the requested quantity η_e, the effective efficiency of the power sensor [2], is determined as ratio of two thermopile outputs, each one corresponding to different thermal equilibrium conditions. Several microcalorimeter designs were developed [1], but the twin type model, as schematized in Fig. 1, reveals to be the most efficient [3]. In this version the thermal load consists of a couple of twin power sensors, one of which is never supplied with HF-power because has to work only as thermal reference.
Originally microcalorimeter was developed for bolometers, resistive power sensors needing a DC-bias. This fixes the working point of the sensors and allows measuring the HF-power by means of the *DC power substitution method* [1]. Bolometers probably will disappear from the market, but they may be substituted more efficiently by thermocouples that already have been successfully used in a CCEM key comparison [5]. Indirect heating thermocouple are not downward frequency limited like bolometers, furthermore they are not so sensitive to the absolute temperature that is a well appreciated feature for a standard. The use of thermocouples is itself an improvement to the microcalorimeter technique therefore. The accuracy of the technique is limited mainly by the parasitic losses on the insulation lines to the range (0.2 – 2.0)%, being the best value obtainable with waveguide mounts or only below 1 GHz about if coaxial power sensors are considered. The diminution of the losses and their consequence on the measurand are not possible by means hardware refinements only, especially in the case of the coaxial lines with small diameter. Therefore, for the increasing of the microcalorimeter accuracy, it is necessary to measure the losses and to correct for their effects on the measurand. All this consists in the microcalorimeter calibration, an operation not trivial because it requires the change of the electrical and the thermodynamic configuration of the system, with the risk to get irrelevant results for the power sensor under calibration. The authors have developed calibration processes that reduce the mentioned risk and along with a more careful data analysis should produce a significant improvement of the microcalorimeter accuracy [5]. In the following we present this process applied to the thermoelectric power sensors.

MICROCALORIMETER CALIBRATION AND MEASUREMENT THEORY

As reported in previous papers [1], [3], [6] the microcalorimeter behaviour is described by the electro-thermal equation:

$$e = \alpha R\left(K_1 P_{inS} + K_2 P_{inL}\right)_{HF} \tag{1}$$

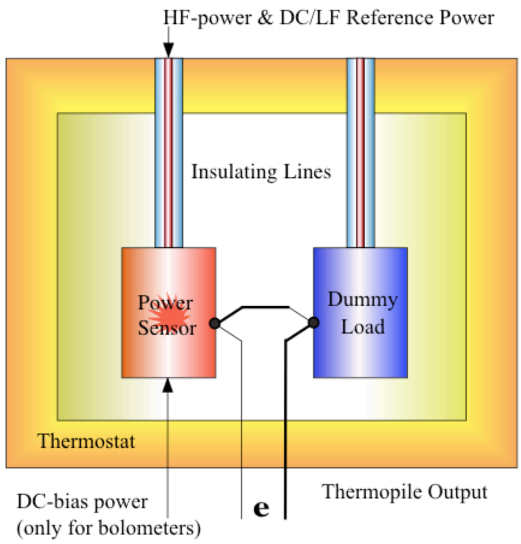

Fig. 1. Twin type microcalorimeter scheme.

It follows as an application of the superimposition principle of the linear effects in our measurement system and e is the thermopile output voltage, P_{inS} the total power dissipated in the sensor mount, P_{inL} the feeding line losses and K_1, K_2 coefficients describing the power separation between sensor and feeding line; α and R are dimensional coefficients that disappear in the following, because only voltage ratios will be considered. When HF-power is supplied to the sensor on the measurement channel (Fig. 2) the thermopile response e_1 is given by (1), while after the substitution of HF-power with DC/ LF-reference power (RE) the thermopile output e_2 will be given by:

$$e = \alpha R \left(K_1 P_{inS} \right)_{RE} \tag{2}$$

This expression results because in DC/LF the losses in the insulating line are negligible. If the power substitution occurs maintaining the output of the power sensor U constant, we can easily obtain a useful expression of the power sensor efficiency η_e taking the ratio of the thermopile outputs e_1 and e_2 at the thermodynamic equilibrium:

$$\eta_e = \frac{e_2}{e_1} \left(1 + \frac{K_2}{K_1} \left(\frac{P_{inL}}{P_{inS}} \right)_{HF} \right) = e_R g \tag{3}$$

So far we defined as *effective efficiency* of a thermocouple power sensor the ratio between a RE-power entering the sensor to the HF-power that produce the same sensor output ($U = const.$), like it has been done in an international inter-comparison [5]:

$$\eta_e = \left. \frac{\left(P_{inS} \right)_{RE}}{\left(P_{inS} \right)_{HF}} \right|_{U = const.} \tag{4}$$

Equation (3) is effective for the power sensor calibration if the term g, dependent on the microcalorimeter characteristics, may be evaluated at each measurement frequency, that is, the measurement system is calibrated. The authors have been showing in [5] that the best microcalorimeter calibration process is obtainable if the power sensor or a twin copy of it can be made a completely reflective HF-load. In this case we can attribute a η_e unitary to it and reversing (3) determine g. Assuming to perform two identical measurement series, one with the sensor in normal condition and the other with the same in highly reflective condition we can have enough information to write:

$$\eta_e = \frac{e_2}{e_1 - e_{1SC}} \tag{5}$$

where e_{1SC} is the thermopile response when the same HF-power producing e_1 is supplied to the power sensor transformed in a virtually reflective load. For obtaining the electrical and thermodynamical conditions that allow writing (5), specifically for thermocouple sensors, we had to modify our microcalorimeter [3]. Two low loss line sections have inserted between the microcalorimeter test-ports and the power sensors realizing the thermal load, Fig. 2. The sections, one of which is a short circuit, are interchangeable between the measurement and reference channel and this allows obtaining the reflectivity condition necessary for calibrating the system without change significantly the hardware configuration of it. The acceptance of (5) is conditioned by the ability to maintain always unchanged the system losses when we change sensor behavior from matched to reflecting. In practice this is possible supplying the HF-power to the microcalorimeter load by means a self-leveled generator.

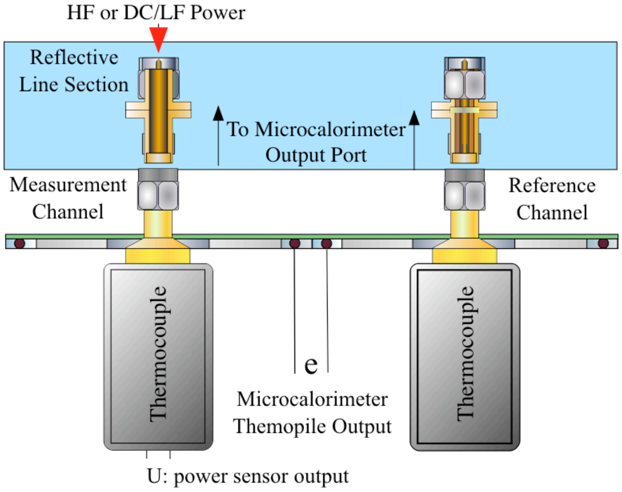

Fig. 2. Details of the twin type microcalorimeter load realized by thermocouple power sensors.

DATA ANALYSIS

Another evolution of the microcalorimeter technique concerns directly the data analysis. If in the past the values e_1, e_2 and e_{1SC} entered (5) were coming from the instrument readings at the thermal equilibrium, now they are more efficiently calculated trough a statistic process. Basically we record the thermopile output continuously when cycling the HF-power with the RE-power, obtaining a saw tooth signal usually distorted and noisy for instrument errors and thermal fluctuations of the system. Then we fit the record with a suitable exponential function whose asymptotes will be the values to enter (5). The very fast Levenberg-Marquardt algorithm has been used as reported in [6]. As input quantities it receives a time base with no associated error and the corresponding thermopile voltage sampling to which a constant error is attributed on the base of n-voltmeter accuracy used to monitor the heating and cooling processes inside the microcalorimeter. We explicitly point out that the HF-power substitution with RE-power corresponds to a system cooling, while contrariwise corresponds a heating, cause the different level of the parasitic losses.
Fig. 3 shows measurement results and fitting results for measurement conditions very critical. At low frequency with the microcalorimeter measurement port terminated by a quite perfect short, the signal e_{1SC} is very low and noisy because very low are the losses of the system. In this case the old technique to use directly the nanovolmeter reading would create problems in choosing the value to enter (5). Another advantage of the adopted analysis concerns the accuracy assessment. The total uncertainty on the measurand η_e is obtained straightforward with the classical error propagation theory applied to (5). Indeed, each term of (5) comes from the fitting with an associated uncertainty, which is the result both of systematic and random components.

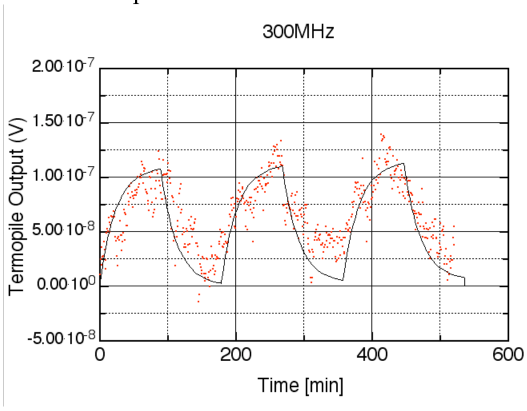

Fig. 3. Typical trend of the microcalorimeter response to injected power when the system losses are very low. Continuous line represents the heating and cooling steps in absence of thermal drifts and noise.

CONCLUSION

We described the last advancements of the microcalorimeter technique. They concern both hardware component and data analysis. A calibration technique previously elaborated for bolometers [6] has extended to thermocouples obtaining a simplified and elegant theory. The data analysis aforementioned in [6] has been extensively applied for realizing new HF-power standards based on thermocouples. The total uncertainty of the HF-power standard should have to be included in the range (0.1-1)% for frequency up to 26,5 GHz and for 3.5 mm coaxial lines, but as no historical record still exists, the validation of the result must wait for a new international comparison at least.

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