A NEW 3.5 mm COAXIAL MICROCALORIMETER:
SYSTEM AND CORRECTION DESCRIPTION

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ABSTRACT

A new microcalorimeter has been realized for implementing the national power standard up to 26.5 GHz in 3.5 mm coaxial line at Istituto Elettrotecnico Nazionale (IEN) Galileo Ferraris. The system is based on a dry thermostatic container whose temperature is controlled by Peltier elements. The thermal load consists of a twin sensor complex that is alternatively supplied with high frequency (HF) and low frequency (LF) or direct current (DC) power through adiabatic coaxial lines. This microcalorimeter has been originally designed for calibrating thermistor mounts fitted with PC 3.5 mm connector, but recently optimized for thermocouple power sensors, which can operate from DC to 26.5 GHz.

INTRODUCTION

The power is a quantity extremely important in the electromagnetic metrology being with the standing wave amplitude the only in reality measurable quantity at high frequency (HF). This stems mainly from the intrinsic nature of the electromagnetic field that does not generally allow a potential function and therefore considering the voltage and the other related electrical quantities like current and impedance in not meaningful [1]. Furthermore, all these quantities are distributed quantities, difficult to measure operatively. Equally important are the HF power standards, whose realization depends always on the calorimeter technique [2].

This technique is fundamental in the realization of the HF primary power standards particularly, because it makes the HF standards traceable to the direct current (DC) standard or to low frequency (LF) standards. The link to these standards is realized and maintained through power sensors calibrated by means microcalorimeters [2].
The standard realization consists mainly in the determination of the effective efficiency [3] of a power sensor mount put inside the microcalorimeter, but it must include the parallel determination of the microcalorimeter efficiency. Without the knowledge of this correction factor, which is strongly dependent on the working frequency, the realization of the power standard is not enough accurate indeed.

The power sensors normally used in the calorimeter technique are of bolometric type, that is, effective value or thermal sensors. Housed both in coaxial and in waveguide mounts, bolometric sensors allow the HF-power measurement through the DC-power substitution method that assumes the equivalence between the thermal effects of DC and HF-power. More or less recently, a new type has been introduced of power sensor that does not work with DC-power substitution method, but it is suitable to be still calibrated by means of microcalorimeter. These sensors are indirect heating thermocouples whose mount however does not house auxiliary electronic as commercial devices do [4]. The main future of this sensor type is the possibility to operate continuously from DC to HF power, a future very useful and appreciated in the calibration environment.

A new microcalorimeter has been designed and realized for implementing the national power standard up to the frequency of 26.5 GHz at Istituto Elettrotecnico Nazionale (IEN) Galileo Ferraris. The measurement system has been originally designed for calibrating classic thermistor mounts fitted with PC 3.5-mm connector, but it is being optimized for thermocouple power sensors previously mentioned, which are the travelling standards used in international comparison CCEM.RF-K10CL (Power Measurement in 3.5 mm Coaxial Line). This new IEN microcalorimeter, compared to the previous one, incorporates some new refinements that improve the global performances of the measurement technique.

SYSTEM DESCRIPTION

The IEN new microcalorimeter is schematized in the Fig. 1 and may be classified as a dry type adiabatic calorimeter. The microcalorimeter core, or thermal load, consists of the sensor mount under test (hot sensor), a device thermally equivalent (dummy sensor) and a thermopile fixture in thermal contact both with hot and dummy sensor. The thermostatization of the core is obtained by means three aluminum (Al) containers, which are separated by polystyrene foam or air and work as thermal shields. The intermediate Al-shield is actively controlled in temperature by means of Peltier elements, while the inner most and outer most shields work as passive thermal filters only, by virtue of their huge thermal capacitance. This thermostat provides a thermal stability that has been measured to be of the order of the mK on the inner most shield. The thermal stability of microcalorimeter inner chamber should be even better, by virtue of the additional contribution to thermal insulation of the massive aluminum third shield. This feature is difficult to measure, because every thermometer placed in the chamber worsens the thermal stability of the environment, cause of the heat flow transported in and out by its leads. A system of twin coaxial transmission lines can supply HF-power or reference (REF) power (DC or 1 kHz) to the device under test (DUT) and to the dummy load if it is requested. Indeed, dummy load, which is never energized and is a cold sensor, may become DUT, it being usually a twin sensor. This is considered for saving time in power sensor calibrations.

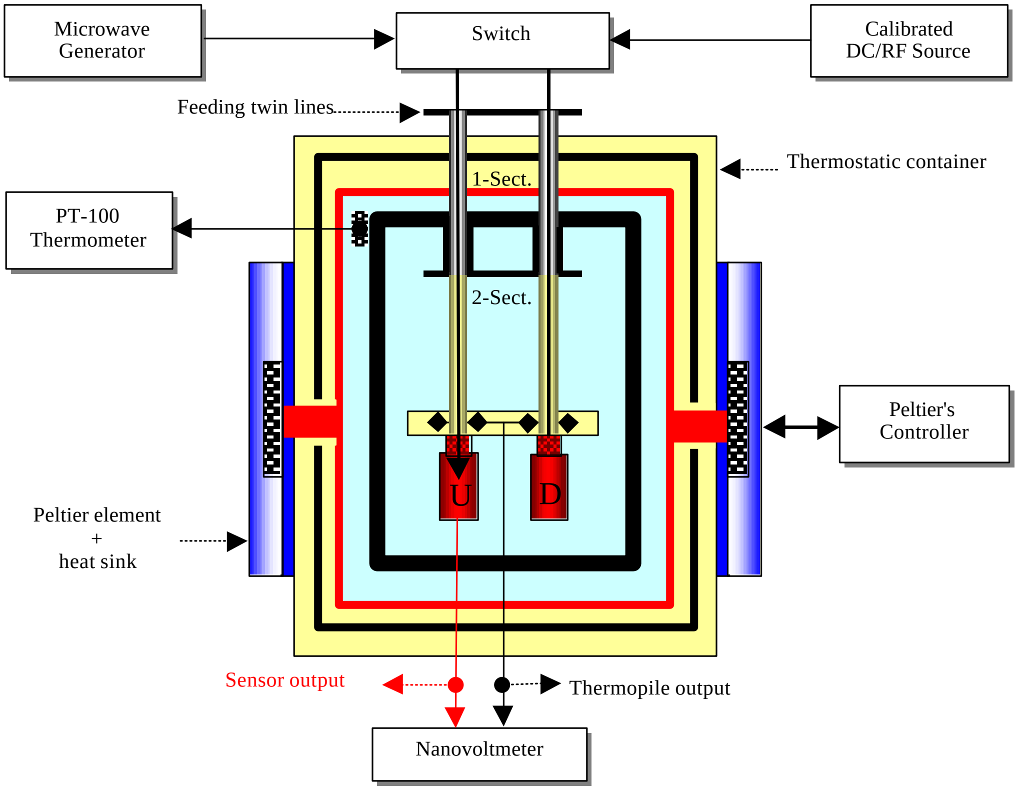

Figure 1. Scheme of the IEN microcalorimeter in 3.5 mm coaxial line

The feeding lines are made of two sections of coaxial line fitted with PC 3.5-mm connectors and exhibiting a high thermal insulation to the external environment. These sections have a common thermal ground on the third shield, but in this system are not symmetric. The section (2-Sect.) nearest to microcalorimeter core has thin wall conductors. Conversely, in the section communicating with the external environment (1-Sect.), only the inner conductor is a thermal insulator, a particular that allows filtering better the thermal noise coming inside from the environment, because thermal noise is more easily conveyed on the thermal ground. The microcalorimeter thermopile is an annular complex of Cu-Constantan junctions that sense the temperature difference between the sensor mount and the dummy load. The system is under computer control and all measurement steps are automatic, except the connection of sensors to the test port.

SYSTEM THEORY

Basically and this independently of the sensor type, the measurement of sensor mount *effective efficiency* h_e is performed by determining the temperature variation of the mount after the HF-power supplied to the DUT in the microcalorimeter has been substituted by an equivalent REF-power. Hereafter, we assume to deal with thermocouple power sensors. Relatively to this sensor type, equivalent power means the power level that maintains unchanged the sensor output U and h_e is defined as ratio of the equivalent REF-power to the HF-power.
Bolometric power sensors had to be considered, the previous definition should be modified [1] to be conformal at the different working principle [3].

After HF or REF-power is applied to the DUT through the feeding line, the thermopile output e begins to follow an increasing or decreasing exponential trend, tending toward finite asymptotes. Only the e-values corresponding to a thermal equilibrium and therefore near the asymptotes are meaningful for our purpose. As these values are obtained after several time constants of the system, they will be named long-time measurements.

The thermopile voltage e, that is proportional to the temperature difference between hot and cold sensor mounts, contains information about power dissipated not only in the hot sensor mount but also in the feeding line system. This additional heat source is not negligible if compared with the mount losses, which define h_e, and therefore the contribution of the feeding line losses must explicitly enter in the calculation. For taking in account this term, the voltage e is splitted in two parts, one related to the power sensor and the other to the feeding line. The following equation may be used to describe our system:

$$e = a\,\Delta T = a\,R\left(K_1 P_{inS} + K_2 P_{IL}\right) \tag{1}$$

where a is the Seebek coefficient of thermopile junctions, R a conversion constant depending on thermodynamic parameters (mass, density and specific heat) of the thermal load, K_1, K_2 coefficients that describe the power separation between DUT and feeding line and $P_{inS,}$ P_{IL} the power dissipated in the sensor and in the insulation line respectively. Equation (1) gives the microcalorimeter response e_1 when HF-power is supplied to the hot mount and the response e_2 when an equivalent REF-power is substituted. Long-time measurements of e_1 and e_2, at condition the DUT output $U = const.$, may be conveniently combined in the following ratio e_R:

$$e_R = \frac{e_2}{e_1} = \left.\frac{P_{inS}\big|_{REF}}{P_{inS}\big|_{HF}}\,\frac{1 + K\left(P_{IL}/P_{inS}\right)\big|_{REF}}{1 + K\left(P_{IL}/P_{inS}\right)\big|_{HF}}\right|_{U=const.} \quad ; \quad K = \frac{K_2}{K_1} \tag{2}$$

Expression (2) may be considered as a measurement of the efficiency of all the system, while the effective efficiency of the power sensors h_e is contained in the last right side of (2). Indeed and according to the previous definition it is:

$$h_e = \left.\frac{P_{inS}\big|_{REF}}{P_{inS}\big|_{HF}}\right|_{U=const.} \tag{3}$$

From (2) and (3), we get the operative formula for the microcalorimeter previously described:

$$h_e = e_R\left(1 + K a_{HF}\right)/\left(1 + K a_{REF}\right) = e_R\, g \tag{4}$$

where a_{HF} and a_{REF} are coefficients related to transmission parameters of the feeding lines. Indeed, it results e. g.:

$$a_{HF} = \left(P_{IL}/P_{inS}\right)\big|_{HF} = \left.\frac{P_{inIL} - \left|S_{21}\right|^2 P_{inIL}}{\left|S_{21}\right|^2 P_{inIL}}\right|_{HF} = \left.\frac{1 - \left|S_{21}\right|^2}{\left|S_{21}\right|^2}\right|_{HF} \tag{5}$$

being P_{inIL} the HF-power entering the insulation line and S_{21} the HF transmission parameter of the same. The parameter g is the *microcalorimeter correction factor* and its determination is a critical operation we describe in the next paragraph as microcalorimeter calibration. The g accuracy contributes almost completely to the total accuracy of the system, especially at HF, where the insulation line losses are of the order of the sensor losses.

MICROCALORIMETER CALIBRATION

The microcalorimeter calibration requires measuring both the transmission parameter S_{21} of the insulation line and the K ratio. The measurement of S_{21} is quite trivial, as it can be carried out with a network analyzer at HF, and with an LRC-meter at the REF-power (DC or 1 kHz). Conversely, the determination of K is a difficult operation because it requires a change of the microcalorimeter normal configuration. Hot sensor and dummy sensor must be disconnected and substituted by two short circuits or open circuits having the same thermal mass and this could change the thermal behavior of the system, leading to an erroneous determination of the separation constants K_1 and K_2. Anyway, interrupting the power supply at the feeding line output, the contribution of K_1 in (1) disappears, that is:

$$e_{1OC} = e_{1SC} = a\,RK_2\,P_{IL}\big|_{HF} = a\,RK_2\left(1-\left|S_{21}\right|^4\right)P_{inIL}\Big|_{HF} \tag{6}$$

$$e_{2SC} = a\,RK_2\,P_{IL}\big|_{REF} \tag{7}$$

The index OC and SC denote the feeding line termination type (open or short). The expression (7) that holds only for a short, otherwise the REF-power could not flow in and out the system, is not useful for thermopile sensitivity limitations if the line losses are too low. When the normal power sensor terminates the insulation line, the contribution of K_2 in (1) may be neglected at the REF-power, because the power P_{IL} dissipated on the line is negligible. Therefore, we may write:

$$e_2 = a\,RK_1\,P_{inS}\big|_{REF} \tag{8}$$

Combining (6) and (8), under the condition the thermodynamic of the system is unchanged, we obtain an estimation of K:

$$K = \frac{e_{1SC}}{e_2}\,\frac{P_{inS}\big|_{REF}}{\left(1-\left|S_{21}\right|^4\right)P_{inIL}\Big|_{HF}} \tag{9}$$

The K estimation may be improved correcting (9) for the contribution of the losses of the insulation line at the REF-frequency and even simplified, maintaining the power level at the insulation line input always constant. Other mathematical approaches that could improve the K-estimation are based on measurements carried out at the REF frequency only [5].

ERROR DISCUSSION

The h_e total accuracy depends on S parameter measurements, power measurements and thermopile voltage measurements. The last ones enter in the error budget directly through (4) and indirectly with (9). Because they typically are low voltage values (order of mV), easily and strongly influenced by the change of thermodynamic conditions of the external environment, give a big error contribution. The microcalorimeter is a differential system well insulated from the environment, but this is not enough to prevent unwanted results on long time measurements of e. The typical thermopile output should be similar to the response of a RC system, with a time constant t = 38 s, to rectangular input pulses, but in practice the output waveform always appears distorted. Therefore the raw thermopile signal is mathematically conditioned and corrected up to obtain the theoretical profile based on microcalorimeter time constant. The long-time voltage measurement e_1, e_2, appearing in the previous chapters, are then substituted by values obtained from the corrected output waveforms.

CONCLUSION

The microcalorimeter here described has been participating to the comparison CCEM.RF-K10CL obtaining effective efficiency measurements between 0.90 and 0.99 in the frequency range 1 kHz-26 GHz for 3.5 mm coaxial power sensors of thermocouple type. The claimed total measurement accuracy is between 0.5% and 2% about, depending it on frequency values, but as the official reference data of the comparison are not yet know we can not consider validated the performance of the new microcalorimeter.

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