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Two Ways of Power Substitution for calibrating Thermoelectric Sensors at RF and Microwaves

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Abstract – **Thermoelectric sensors reached a dominant application in the commercial power meters at Radio Frequency (RF) and Microwaves (MW), by virtue of their superior robustness, stability and accuracy if compared with other types of power sensors. Furthermore, their performances reveal to be very useful in the realization of broadband primary power standards as a valid alternative to the resistive sensors, i.e. bolometers, in coaxial transmission line, at least. Recent technological improvements allow thermoelectric sensor calibration following two circuital schemes. In simple words, sensors have been fitted with auxiliary absorbers to which direct current (dc) reference power can be supplied as an alternative to their main RF/MW absorber. Hereby, we present a comparison in term of effective efficiency of a thermoelectric sensor that is calibrated with the calorimetric technique and by using the two possibilities of power substitution. The aim is to verify to what extent the two calibration ways can be considered equivalent.**

Keywords – **Microwaves, power standards, power substitution, microcalorimeter, thermoelectric sensors.**

I. INTRODUCTION

Realization of the primary power standards at Radio Frequency and Microwave (RF and MW) has always been an important challenge for all National Metrology Institutes (NMIs).

The technique used by these institutions consists in calibrating a thermal detector against the *dc power standard* by means of the power substitution method [1], [2]. The process dates back to the late 1950's and it is still without alternatives, even though improvements have been introduced during the last decades [3], [4].

Anyway, a significant change consists in the use of the thermoelectric detection rather than original bolometric one [1]. This has been firstly suggested by the difficulty to find commercial bolometric sensors, but from a technical point of view, it should be most motivated by the superior performances of the thermoelectric sensors. This fact has been demonstrated even by the same authors, for the coaxial case at least, [4] – [6].

Recently a broadband power standard has been realized by means of a thermoelectric sensor fed with a hybrid transmission line that allows TEM mode propagation from dc to 110 GHz, [7].

However, an interesting characteristic of the device used in [7] consists of an additional auxiliary heater, fitted back to back with the RF-MW absorber, but electrically insulated from it. The purpose of such advanced architecture is that to provide a specific way for the sensor self-calibration.

De facto, this offers also an alternative way with which to supply the reference power into microcalorimeters that use thermoelectric power sensors as calorimetric loads; these ones are presently energized only through the main RF- MW coaxial line [4]. A first application of this method has been demonstrated in [8].

While in [8] the *effective efficiency* of the device was found, for a waveguide system, in a non-standard way, in this paper we demonstrate that it can be measured with the standard microcalorimetric technique. In coaxial systems like ours, it can be determined by following two different ways, that is, by supplying reference dc-power to the RF/MW absorber or in alternative to the auxiliary heather.

This said, our aim is to evaluate to what extent the *effective efficiency* values obtained by the two different power substitutions are consistent one to the other. We start assuming that a thermoelectric power standard can be only associated to a unique value of effective efficiency, therefore it is worth investigating whether or not this value can be indifferently obtained in the two modes.

The paper presents the calibration of a power

sensor of the type mentioned in [7] at some spot frequencies in the 0.01–18 GHz band. Measurements are performed with INRIM coaxial microcalorimeter by using the two different circuital schemes for power substitution.

II. DEVICES AND THEORY

In our experiment we consider a commercial thermoelectric sensor in coaxial line, which has been fitted by the manufacturer with dc-auxiliary heather, as Fig. 1 shows. This electric scheme has been designed to have a specific feeding path for self-calibrating the device when connected to a commercial power meter. In our case we want to use it for realizing a primary transfer standard by means of the microcalorimeter technique [1], [2], [3].
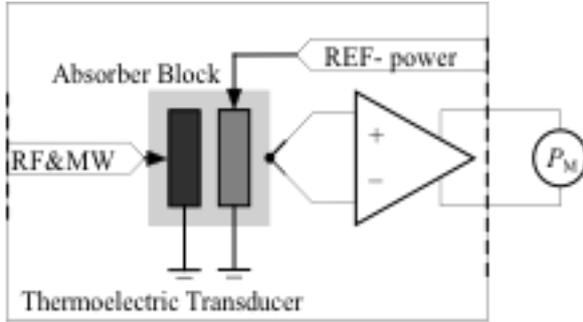

Fig. 1. Scheme of the thermoelectric power sensor considered for the microcalorimeter calibration.

The quantity that characterizes the device and that we want to measure is the effective efficiency η_e of the sensor mount, usually defined by:

$$\eta_e = \frac{P_{dc}}{P_{RF}} | U_{dc} = U_{RF}, \qquad (1)$$

that is, by the ratio of the reference dc-power to total RF/MW power dissipated in the mount, each one producing the same sensor response $U_{dc} = U_{RF}$.

As the dc-power substitution can be done trough two different transmission lines, it is interesting to verify which different sensor behaviors exist connected to different thermal paths followed by P_{dc} and P_{RF}.

Because (1) implies that the following conditions hold:

$$\frac{P_{dc}}{H_{dc}} = U_{dc} = U_{RF} = \frac{P_{RF}}{H_{RF}}, \qquad (2)$$

where H_{dc} and H_{RF} are quantities dependent both on feeding line thermal properties and on the

electromagnetic field dissipation inside the absorber block, then the effective efficiency can be expressed in term of previous quantities:

$$\eta_e = \frac{H_{RF}}{H_{dc}}. \qquad (3)$$

Evidently H_{dc} in not equal to H_{RF} cause unequal dissipation of the electromagnetic fields in the absorber block, but whereas H_{RF} is unicum, H_{dc} can differ if power substitution is made into RF/MW absorber or into auxiliary heater. Experiments here described show that H_{dc} is reasonably not sensitive to the change of the power substitution paths, of course in the limit of the instrumentation sensitivity. This means that main absorber and auxiliary heater are both well thermally matched to sensor thermometer, i.e. internal thermocouple schematized in Fig. 1.

Though, on the bases of previous deductions we can say that (3) returns only one effective efficiency value independent of the power substitution way selected, it is not possible to know this value because both H_{RF} and H_{dc} cannot be directly measured.

Therefore we must proceed by using the technique developed at INRIM for realizing a RF/MW power standard based on thermoelectric sensor in coaxial line [9]. The η_e is now defined in a more general way as ratio of measured power P_M to the total absorbed power $P_A = (P_M + P_X)$ by the same sensor:

$$\eta_e = \frac{P_M}{P_M + P_X}, \qquad (4)$$

where P_X is the power loss in the sensor mount.

As thoroughly described in the literature by the same authors [4] − [6], starting from this definition we deduce a formula that allows an effective measurement of η_e, that is:

$$\eta_e = \left(\frac{e_2}{e_1} \right) \left[1 - \left(1 + |\Gamma_S|^2 \right) \frac{e_{1SC}}{2e_1} \right]^{-1}, \qquad (5)$$

where e_1 and e_2 are the electrical responses of the microcalorimeter to the RF-MW power and to the reference dc power substituted into the system, respectively. The voltage e_{1SC} corrects the microcalorimeter response for system losses and is determined by means of measurement with the microcalorimeter test port in short circuit condition [4], [9].

Finally, the term $(1+|\Gamma_S|^2)$ is an additional correction necessary to enhance the result accuracy when the reflection coefficient Γ_S of sensors under calibration is not negligible [10]. Equation (5) can also

be corrected to take into account possible short circuit losses [11].

III.   MEASUREMENT RESULTS

Experimental work consists in the calibration of a specific thermoelectric sensor mount fitted with a PCN connector at spot frequencies in the band 0.01–18 GHz by means of the INRIM coaxial microcalorimeter, [6]. The device under test has been derived from a commercial item modified for being efficiently used as microcalorimeter thermal load.

Calibrations has been performed according to the INRIM protocol, that requests to operate in a shielded and thermostatic environment at $(23 \pm 0.3)°C$ with relative humidity of $(45 \pm 5)\%$.

Once selected a measurement frequency, the system is supplied at the nominal power of 1 mW for a total time of 1200 min. Each measurement cycle begins by supplying the thermoelectric sensor with RF/MW power for 400 min. After such time interval the RF/MW is substituted with a dc power level that produces a constant sensor response. Then, the same dc power level is maintained for 800 min until a new frequency value is set.

At each frequency step the microcalorimeter thermometer, i.e. a thermopile, generates a signal of the order of some µV and of the form reported in Fig. 2, [6].
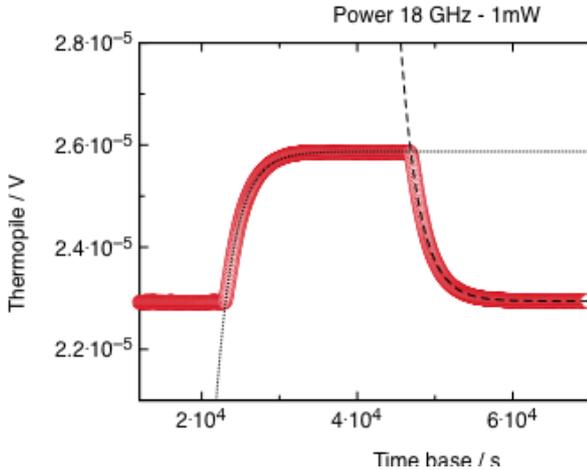

Power 18 GHz - 1mW

Fig. 2. Typical microcalorimeter response to a power substitution of 1 mW on a thermoelectric sensor used as calorimetric load.

With reference to Fig. 2, when RF/MW is supplied to the calorimetric load, the system thermometer measures an exponential temperature increase of the same load up to an asymptotic value e_1. Conversely when RF/MW is substituted with a thermally equivalent dc power, there is a cooling of the thermal load down to another asymptotic value e_2.

Temperature increasing is proportional to the parasitic losses at RF/MW of calorimetric load, whereas the asymptote e_2 is a measure of the equilibrium temperature the system reaches in absence of losses. A similar behavior occurs when the system is short-circuited to find e_{1SC}.

A fitting process based on the Levenberg – Marquardt algorithm has been used to obtain the asymptote values e_2, e_1 and e_{1SC} from measurements, together with the uncertainty component related to the thermometer accuracy [12]. In Table 1 we give two values of η_e calculated with (5) for each measurement frequency so to highlight what discrepancy exists between the two methods of power substitution. Expanded uncertainty (coverage factor $k = 2$) is also reported. The uncertainty sources are that arising from the fitting procedures, the thermal instability of the system and the sensor reflection coefficient. The whole measurement uncertainties associated to the measurand η_e have been calculated by applying the Gaussian error propagation, so to be conformal with [13].

From these data it is immediate to recognize that the substitution paths are equivalent. Therefore we have experimentally demonstrated that, for this specific kind of sensors, the effect of the power substitution results independent of the mode it is performed, that is directly on the RF/MW absorber or on the dc auxiliary heater.

Table 1. Calibration points of thermoelectric power standard; case (a): power substitution on coaxial line; case (b): power substitution on auxiliary heather.

Freq. (GHz)	η_e case(a)	$U(\eta_e)$ $k = 2$	η_e case(b)	$U(\eta_e)$ $k = 2$
0.05	0.9967	0.0010	0.9949	0.0012
1	0.9879	0.0009	0.9866	0.0010
10	0.9543	0.0007	0.9532	0.0009
18	0.9391	0.0010	0.9385	0.0010

IV.   CONCLUSIONS

From the technical point of view the significant achievement consists in the realization of a broadband primary power standard (0.01 – 18 GHz) by applying a conventional measurement procedure to the INRIM coaxial microcalorimeter to a novel type of load. Basically, we used as calorimetric load a new type of thermoelectric sensor fitted with two absorbers electrically independent, but supposed thermally equivalent. This sensor architecture required hardware arrangements into the measurement system, but allowed to apply the power substitution method in two different modes.

The sensor has been calibrated two times in the frequency range 0.01 – 18 GHz. One calibration has been performed according to the classical procedure

used at INRIM, that is, by supplying the reference dc power directly on the input coaxial line. In a second step the calibration has been repeated by energizing the auxiliary heater with the same amount of dc power.

The results of the calibrations are coincident and, in the limit of the measurements uncertainty, generate a unique value of effective efficiency at each calibration frequency. This verifies experimentally the equivalence of the two procedures and, indirectly, the high quality manufacturing of the new sensor architecture.

However there is a more important outcome that must be highlighted, that could have strong impact for the primary metrology in the RF/MW field and also beyond. Indeed, because the thermoelectric sensors can be now calibrated trough an auxiliary heater that is electrically independent of the main absorber, then they can be used to realize hollow waveguide based primary power standards by using standard microcalorimetric procedures.

In other words, having experienced lack of bolometric devices on the market, the microcalorimeter technique finds finally a suitable load for being extended to 110 GHz and beyond, where the coaxial technology cannot be easily used.

V. ACKNOWLEDGEMENT

REFERENCES

[1] N. S. Chung, J. Sin, H. Bayer, and R. Honigbaum, "Coaxial and Waveguide Microcalorimeters for RF and Microwave Power Standards," IEEE Trans. Instr. and Measurements, vol. 38, no. 2, pp. 460-464, April 1989, DOI: 10.1109/19.192327.

[2] A. Fantom, Radiofrequency & microwave power measurement, London, UK: Peter Peregrinus Ltd., 1990.

[3] E. Vollmer, J. Ruhaak, D. Janik, W. Peinelt, W. Butz, D. Stumper, "Microcalorimeter Measurement of the Effective Efficiency of Microwave Power Sensors Comprising Thermocouples," CPEM 1994 Conf. Digest, pp. 147-148, 1994, DOI: 10.1109/CPEM.1994.333409.

[4] L. Brunetti, E. Vremera, "A new microcalorimeter for measurements in 3.5-mm coaxial line", IEEE Trans. Instr. Meas., vol. 52, No. 2, pp. 320–323, Apr. 2003, DOI: 10.1109/TIM.2003.810047.

[5] L. Brunetti, L. Oberto, M. Sellone, E. Vremera, "Comparison between Thermoelectric and Bolometric Microwave Power Sensors," IEEE Trans. Instr. and Measurement, vol. 62, no. 6, pp. 1710-1715, June 2013, DOI: 10.1109/TIM.2013.2253914.

[6] L. Brunetti, L. Oberto, M. Sellone, N. Shoaib, E. Vremera, "Improvements on INRIM Coaxial Microcalorimeter and Outcome of a Model Comparison", IEEE Trans. Instr. and Measurement, vol. 64, no. 6, pp. 1742-1746, June 2015, DOI: 10.1109/TIM.2015.2406052.

[7] T. Reichel, "Power sensor with 1 mm coaxial connector covers the frequency range from DC to 110 GHz", Rohde & Schwarz NEWS, vol. 208, pp. 23-25, May 2013.

[8] R. Judaschke, K. Kuhlmann, T. Reichel, W. Perndl, "Millimeter-Wave Thermoelectric Power Transfer Standard", IEEE Trans. Instr. and Measurement, vol. 64, no. 12, pp. 3444-3450, Dicember 2015, DOI: 10.1109/TIM.2015.2454632.

[9] L. Brunetti, L. Oberto and E. Vremera, "Thermoelectric sensor as microcalorimeter load", IEEE Trans. Instr. Meas., vol. 56, no. 6, pp. 2220–2224, Dec. 2007, DOI: 10.1109/TIM.2007.908135.

[10] L. Brunetti, L. Oberto, M. Sellone and E. Vremera, "Latest determination of a coaxial microcalorimeter calibration factor", Meas. Sci. Technol., vol. 22, no. 2, pp. 025101-6, Dec. 2011, DOI: 10.1088/0957-0233/22/2/025101.

[11] L. Brunetti and L. Oberto, "On coaxial microcalorimeter calibration", Eur. Phys. J. Appl. Phys., vol. 43, no. 2, pp. 239-244, 2008, DOI: 10.1051/epjap:2008116.

[12] W. H. Press, B. P Flannery, S. A. Teukolsky and W.T. Vetterling, Numerical Recipes − the Art of Scientific Computing, Second Edition, University Press, Cambridge, 1992.

[13] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML, Guide to the Expression of the Uncertainty in Measurement, 2nd ed. 1995, available online: http://www.bipm.org/en/publications/guides/gum.html.