

Characterization of adiabatic lines for twin-microcalorimeters design

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Abstract-The paper presents the methods used for realizing and characterizing the insulating lines of twin broadband microcalorimeters. Both thermal and electrical measurements have been applied, together with electro-thermal modelling, to insulating coaxial line assemblies of different type from *dc* to 40 GHz.

I. Introduction

The calibration of the power sensors is a result of time consuming and complicated measurements. For standard power sensors, but not only in this case, microcalorimetry is the only calibration technique available [1], [2]. Coaxial microcalorimeters are measurement systems developed for broadband power sensors, cause of the fast progress in extending the working frequency limit of the coaxial devices at several tens of GHz. The critical differences from the waveguide case are due to the presence of the inner conductor and of some dielectric parts in the feeding lines that alter the thermal and the electrical fluxes in a mode that cannot be fully characterized. Coaxial microcalorimeter is less accurate than the waveguide version, therefore it is still necessary to improve its hardware and modelling, even by means of additional measurements and data analysis. The term “adiabatic”, often hereby used, corresponds to the status of perfect thermal insulation, that is, a condition never reachable in practice, though the twin-structure offers a powerful way for solving the problems created by the imperfect thermal insulation of the system [3], [4].

A. Microcalorimeter loads

Microcalorimeter load is every device that converts electromagnetic power into heat, but the typical load consists of the power sensor of which we are interested to measure the effective efficiency. The effective efficiency measurement of bolometric power sensors has been the main object in using the microcalorimeter since ever, but the same parameter can now be also measured for the thermoelectric power sensors [4]. The main difference between these two sensor types consists of a *dc* self-balancing bias that fixes the working point of the bolometer and then the temperature of its case. In other words, the bolometric sensor is a device that works at constant power level and therefore at constant temperature, also. Conversely, thermoelectric power sensors do not require a *dc* bias power and the dissipated power in it is only dependent on input high frequency power. In the first case the developed heat is almost constant; in the second one it is variable. For bolometric power sensors the reference power, that is, the power at which the effective efficiency is supposed equal to 1 is obtained from a *dc* biasing current [1], [3], while for the thermoelectric ones can be in *dc* or *ac* and even at audio frequency [4]. An important parameter of the microcalorimeter coaxial loads is represented by the magnitude of their mismatches. The interaction between the forward and backward waves results in a variable heat development along of the feeding lines, especially at upper frequencies, that disturbs the effective efficiency measurement. This effect is more critical when we have to use full reflecting loads (e. g. short-circuits) for the microcalorimeter calibration, because in this case both incident and reflected waves have about the same magnitude. Other parameters that influence the thermal behaviour of the system are: thermal time constant, thermal diffusivity and the thermal capacitance [5]–[9]. The twin configuration [4] realizes a differential system that does not require a deep investigation of the phenomena related to previous parameters. In any case, it still remains to study the influence on the measurements of the load surface, its thermal emissivity and the mechanical coupling of the line sections.

B. Microcalorimeter coaxial feeding lines

The broadband microcalorimeter is provided with coaxial line insets, composed of several sections, each one having specific roles [1]–[4]. The insets, two for twin-configuration, have to supply hf power to the inner loads, possibly without power losses and providing high thermal insulation. Unfortunately, these two behaviours act in opposite directions: a good power transmission means a poor thermal insulation.

A feeding line consists of low loss transmission sections, thermal insulation sections, switching sections, adapters and interconnection sections [1]–[4]. Depending on the upper working frequency, the external conductor has standardized diameters of 7 mm, 3.5 mm, 2.92 mm and 2.4 mm, while the inner conductors have the appropriate diameters so to obtain always a characteristic impedance of 50Ω . The upper working frequency increases with the decreasing of the line diameter. Above 18 GHz, the dimension of inner conductor becomes so small that the machining becomes too difficult to do with required accuracy.

The thermal parameters of the feeding path sections differ in accordance with the dimensions of the line, them being better for small sizes, of course. Figure 1 shows a section of 2.92 mm feeding line which is suitable for working up to 40 GHz.

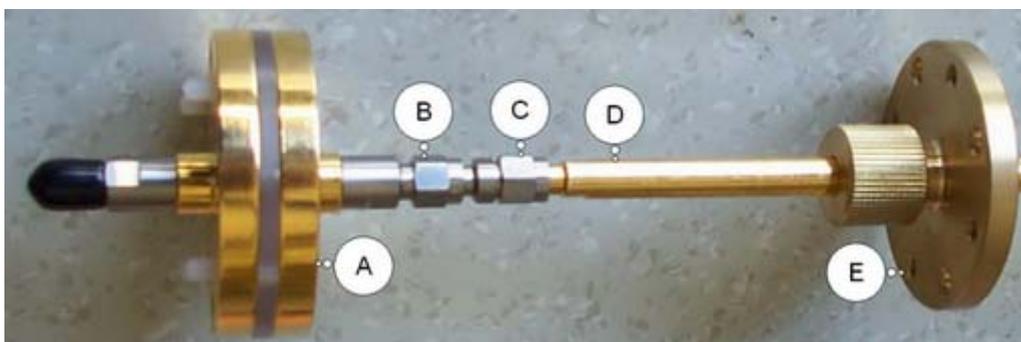


Figure 1. Partial view of a 2.92 mm feeding line; A = Insulated section assembly; B = Connector; C = Adapter; D = 2.92 mm airline E = Mechanical anchorage and thermal shunt.

II. Insulated lines

Due to the small dimension of the inner conductor, an efficient thermal insulating section can be realized by acting only on the external conductor. As the cross-section of Figure 2 a shows, the thermal insulation is provided mainly by a hollow ceramic cylindrical 5 having a thin film metallization 6 and being axially encapsulated between two bulk metallic flanges 1 - 2 by means of the plastic bolts and spacers 7 - 8. The thickness of the metallized wall 6 must assure low insertion losses and poor thermal conduction while the hollow cylinder must have good mechanical and thermal characteristics, that is, low thermal conduction, very small porosity, low expansion coefficient, and low elastic elongation factor [5]–[10]. The flanges thermal shunting, due to the spacers and bolts, is reduced by means of the small spacers 8 and the presence of an intermediate thermal insulator ring 3 in the second flange 2 - 4.

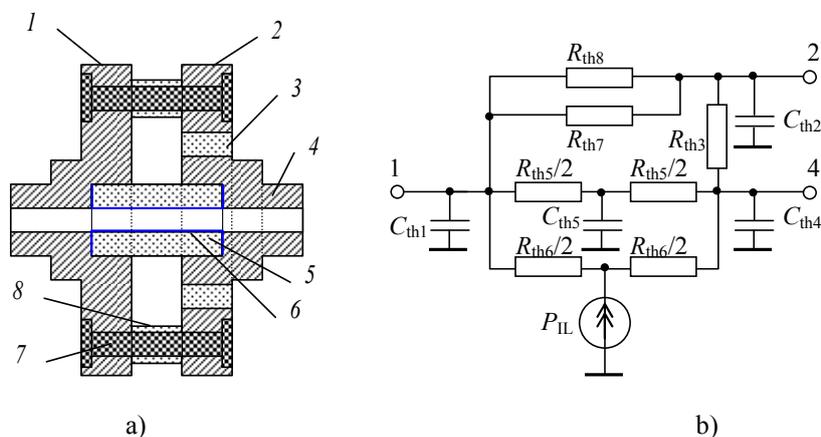


Figure 2: a) - Insulating line cross-section; b) - Dual electrical scheme of insulating line.

The realization of such an insulating line, usually named “adiabatic line”, requires many steps. For obtaining the complex flange 2 - 4 it is necessary to start from two flanges type 1, axially aligned and encapsulating a ceramic cylinder together with proper spacers and bolts. Then, an additional insulating ring 3 is obtained by means of metal discharging and cast resin substitution. Finally, the whole assembly is drilled, internally refined and silver plated up to obtain the appropriate inner surface. Aging and trimming of the conductive layer thickness will produce the correct value of dc resistance of which the function we will explain in the following. Thermal and electrical measurements allow characterization of the external conductor of the insulating line that can be conveniently represented by means of a dual electrical model [5] as Figure 2 b shows.

In such a representation, some components are omitted, as thermal capacitance C_{th6} of the thin metal wall 6, or the thermal capacitance of the plastic parts (3, 7 and 8). The thermal resistance of the metalized wall described by R_{th6} is the smallest of all others represented in Figure 2b. It is related to the acceptable upper limit for dc resistance, which should be below 0.3Ω . To obtain this, a thickness less than $5 \mu m$ is requested, if pure silver is used for an insulator 9 mm long in 2.92 mm standard line. The insertion losses in this section (P_{IL}) depend on this thickness and the quality of the surface. The terminals 1, 2 and 4 in the equivalent electrical model of Figure 2 b, corresponding to the metallic parts of Figure 2 a, can be used to determine the behaviours of the complex. In the normal experiment, that is, inside the microcalorimeter, 1 is coupled directly to an infinite wall having a constant reference temperature, 2 can be floating or can be coupled to a guard shield, 4 is connected to the microcalorimeter load in which the main part of the heat is developed, while P_{IL} is distributed along the line. When the insulating assembly is tested outside the microcalorimeter, 1 is connected through a coaxial line section to an infinite wall having room temperature, 2 is floating and 4 is connected through another coaxial line section to a load able to convert the electrical power into heat.

III. Measurements and results

Measurements were performed on different samples of insulating line sections. The diversity of them consist in the type of the insulators, materials used in their machining, presence or absence of the insulator gap 3 in the second flange, presence or absence of the metalized wall, a.s.o. The measurements mentioned above were performed with suitable instrumentation set-ups, which allowed also to accelerate the aging and to measure its changing rate. Only two type of measurement will be however described in this paper.

A. Thermal measurements

Usually, these measurements aim to obtain the thermal diffusivity, while the thermal conductivity (or resistance) of the line is obtained from the former quantity [5], [6], [9], [11]. Figure 3 shows schematically the instrumentation set-up used to determine the thermal behaviours of an insulating line section. The measurement sequences calls for a succession of power - no power applied to the load through the transmission line that includes an insulating section. To determine the temperature of its external surfaces, T_1 , T_2 , two thermistors were placed tightly on the surface, and the values of their resistances measured with two ohmmeters.

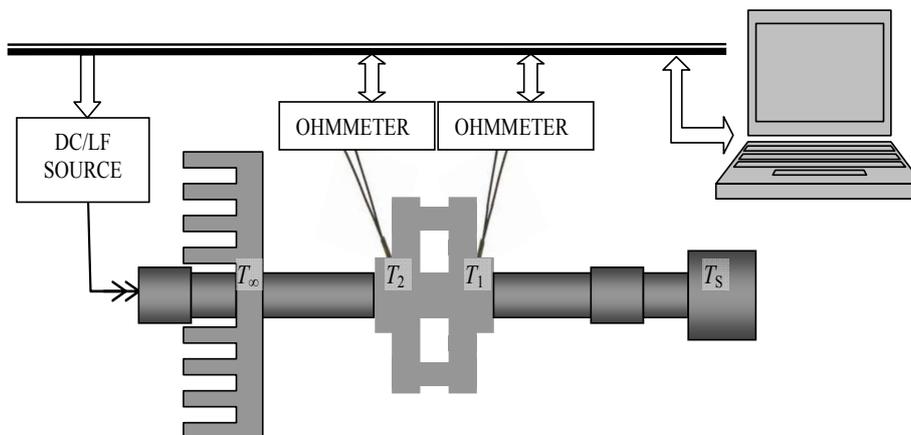


Figure 3. Instrumentation set-up for thermal behaviours measurement.

The sampling rate was 10 s, while the semi-cycles (power-on/power-off) of one hour. Every mount was measured in quite similar conditions for three complete cycles. The raw data are resistance versus time while

computed data provide temperature based on the correspondence table of the MBD thermistors. Figures 4a and 4b show two graph families obtained for two different compositions:

1- Plexiglas [3], [9] single spacer, as A in Figure 1, and cylindrical miniature polycarbonate four spacers as 8 in Figure 2, [6]–[8];

2- Macor [10] metalized as 5 in Figure 2 and not metalized polycarbonate cylinder of same dimensions.

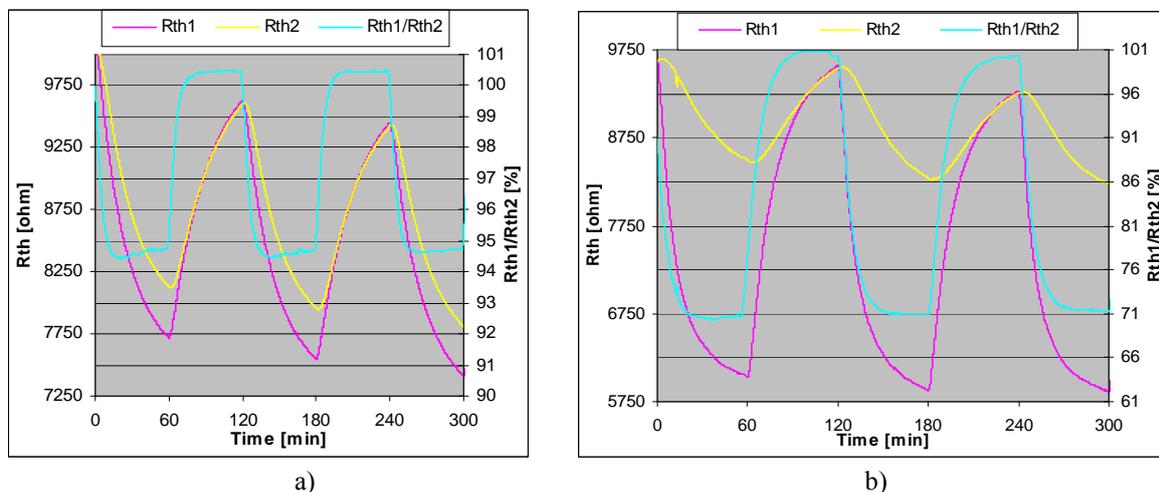


Figure 4: Results of thermal measurements with temperature sensors; a) insulating line part 5 realized in Macor silver plated; b) insulating line part 5 realized in not metalized polycarbonate.

Translated in the corresponding temperature, these data show an increasing of the equivalent thermal resistance R_{th14} from 2.3 K/W to 15 K/W when we substitute silver plated Macor with Polycarbonate insulator. This means a possible improvement of the thermal insulation of more than 6 times. When the polycarbonate thermal insulator was metalized in order to obtain an electrical resistance of 0.3Ω – below 1% from the characteristic impedance of the coaxial line, the equivalent thermal resistance R_{th14} decreases at about 10 K/W due to the value of R_{th6} around of 32 K/W. Anyway, this still means an improvement in the thermal insulation of more than 4 times.

The contribution of the inner conductor cannot be measured, but it is possible to be calculated based on the geometrical dimensions and its thermal conductivity κ , [5]:

$$R_{th} = \frac{\ell}{\kappa\pi(r_{ext}^2 - r_{int}^2)} = \frac{4\ell}{\kappa\pi(d_{ext}^2 - d_{int}^2)}. \quad (1)$$

The inner conductors were gold plated brass or stainless steel tubes, defined by geometrical dimensions: r_{int} or d_{int} , r_{ext} or d_{ext} and the length ℓ . The thermal resistance R_{th} - computed for the same length as the insulator 5 in Figure 2 - has resulted between 120 K/W and 800 K/W. This shows that the outer conductor is mainly responsible for the thermal isolation.

B. Electrical measurements

The first measured electrical parameter is the dc - lf resistance, performed by means of an instrumentation set-up similar to that of Figure 3. Ohmmeters are replaced by voltmeters, the load is replaced with a coaxial short-circuit, the power source is working in constant-current mode, while the infinite wall is missing. The voltage drop that is related to the silver layer resistance is sampled and recorded for long time. When this record shows that the aging rate becomes insignificant, the measurement is stopped and another process starts in order to trim the thickness of this metalized layer on the base of the actual electrical resistance value. The adjustment is stopped when the electrical resistance between flanges 1 and 4 grow to be the imposed value, i.e. $300 \text{ m}\Omega$. Thus, the thickness of the Silver layer, δ in the Figure 2 a, is enough well estimated based on the computing equation in a cylinder case:

$$\delta = \sqrt{\left(\frac{d}{2}\right)^2 + \frac{\rho}{R_{el}} \cdot \frac{\ell}{\pi} - \frac{d}{2}}, \quad (2)$$

where δ is the metalized wall thickness, d is the coaxial line inner diameter, R_{el} the imposed electrical resistance of the insulated line sections, i.e. $300 \text{ m}\Omega$, ℓ is the length of the insulated piece 5 and ρ is the electrical specific conductance of the metal used for realize δ in Figure 2 a, i.e. $1.1 \mu\Omega\cdot\text{m}$ (at 20°C) for Silver Compound Paint.

Next step is the device characterizing by means of S -parameters measurement. In the first instance, only S_{21} is important, but even the reflection parameter S_{22} will be implied in evaluation of the insertion losses and return losses [12], [13]. Indeed, it seems appropriate to characterize the insulating section through the losses to transmitted power ratio p_{IL} , that is:

$$p_{IL} = \frac{P_{IL}}{P_t} \approx \frac{(1 - S_{21}^2)(1 + S_{21}^2 S_{22}^2)}{S_{21}^2 (1 - S_{22}^2)}. \quad (3)$$

The best balanced insulating line pair, designed to operate in dc - 40 GHz band, has presented a span of 1.90% for the parameter defined in (3). It is assumed that below $\pm 1\%$, this ratio implicates a good symmetry in the twin-microcalorimeter, opening so the way for the fast measurement methods described in [14].

IV. Conclusion

The difficulties in realizing a coaxial insulating inset, able to work from dc , are related mainly to the thermal behaviours. Increasing of the thermal resistance is possible in first instance by a proper design of the outer conductor. Decreasing in the thickness of the metalized film is possible but without to reduce too much the transmission parameters, in order to avoid great losses in it. A twin of insulating insets can be considered good if is characterized by differences below one percent in the new introduced parameter $\Delta p_{IL(\%)}$; this assumes both thermal insulation and electrical power transmission closely matched at the same time. Study of the thermal behaviours of component by means of dual circuits allows the use of a powerful investigation tool for obtaining the transient and the log-term system responses. The involved parameters can be obtained from complicated calculus based on the components specifications as material and geometric shape and size, or from measurements as the ones described in this paper. The proposed process for realizing improved microcalorimeter insets opens the way for obtaining a balanced and thermally insulated broadband microcalorimeter that approaches well the perfect adiabatic system.

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References

- [1] Fantom, A., *Radiofrequency & microwave power measurement*, Peter Peregrinus Ltd, 1990.
- [2] Glenn, E. F., *Microwave circuit theory and foundations of microwave metrology*, Peregrinus Ltd., 1992.
- [3] Chung, N. S., et al., "Coaxial and Waveguide Microcalorimeters for RF and Microwave Power Standards", *IEEE Transactions on Instrumentation and Measurement*, vol. 38, no. 2, pp. 460-464, 1989.
- [4] Brunetti, L. and Vremera, E., "A new microcalorimeter for measurements in 3.5-mm coaxial line", *IEEE Transaction on Instrumentation and Measurement*, vol. 52, no. 2, pp. 320-323, 2003.
- [5] Meijer, G.C.M. and Herwaarden, A.W. (Ed.), *Thermal Sensors*, Inst. of Physics Publishing, Bristol, 1994.
- [6] Hatakeyama, T., Quinn, F.X., *Thermal Analysis: Fundamentals and Applications to Polymer Science*, John Wiley & Sons Ltd., 1999.
- [7] Harper, Ch. (Ed.), *Electronic Materials and Processes Handbook*, McGraw-Hill, 2004.
- [8] Chen, L. F., et al., *Microwave Electronics Measurement and Materials Characterization*, John Wiley & Sons Ltd., 2004.
- [9] Menczel, J. D. and Prime, R. B. (Eds.), *Thermal Analysis of Polymers: Fundamentals and Applications*, John Wiley & Sons Ltd., 2009.
- [10] Carter, C. B. and Norton, M. G., *Ceramic materials: science and engineering*, Springer LLC, 2007.
- [11] Webster, J. G. (Ed.), *Measurement, Instrumentation, and Sensors Handbook*, CRC Press, 1999.
- [12] Davidovitz, M., "A Low-Loss Thermal Isolator for Waveguides and Coaxial Transmission Lines" *IEEE Microwave and Guided Wave Letters*, vol. 6, no. 1, pp. 25-27, 1996.
- [13] Hesler, J. L., et al., "A Broadband Waveguide Thermal Isolator", The International Symposium on Space THz Technology, Tucson AZ, pp. 1-7, April 2003.
- [14] Vremera, E., Brunetti, L. et al., "Alternative Procedures in Realizing of the High Frequency Power Standards with Microcalorimeter and Thermoelectric Power Sensors", *Measurement*, vol. 42, no. 2, pp. 269 - 276, 2009.