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STUDY ON THIN-FILM THERMOPILES IN MICROCALORIMETER APPLICATIONS*

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Abstract

Microcalorimeters are special devices used for effective efficiency measurements of bolometric power sensors. Performances of the microcalorimeters, such as sensitivity and accuracy, are mainly dependent on the thermoelectric detector. They are improved using thin-film thermopiles (copper-constantan or nickel-chrome) as an alternative to the traditional thermopile with bulky junctions. Description and related experimental results concerninga thin-film thermopile specially designed for a microcalorimeter are reported.

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Introduction

The link between the fundamental electrical quantity, i.e. the direct current, and all the electromagnetic quantities that are used in high-frequency (HF) metrology, is realized by calorimetric systems. Such systems are used to establish the standards of the HF-electromagnetic power, the main HF-quantity, and more often to measure an important parameter of the bolometric power detectors reported as "effective efficiency".

Generally, in HF-metrology, the term calorimeter refers to a system used to measure absolute electromagnetic power, while the term microcalorimeter refers to specialized devices adjusted to measure energy rate or "effective efficiency" of bolometers, according to its definition |1|.

An exhaustive description of calorimeter and microcalorimeter, including their use, may be found in the specialized literature |2|,|3|,|4|,|5|,|6|,|7|,|8|. However a brief summary concerning the microcalorimeter principle is also given in this paper to clarify the role of the thermopile in such measurement systems.

In the microcalorimeter the thermopile detects the parasitic thermal losses appearing when the electromagnetic power is applied to the bolometer mount working as thermal load of the system. The losses which depend both on effective efficiency and on HF-power level applied to bolometer mount, may be sometimes below the μW-level. Fig. 1 shows the trend of bolometric losses P_x versus effective efficiency η_e for typical values of HF-power P measured by a bolometer power detector. The thermal effect produced by the parasitic losses is a temperature increase on the bolometer mount that varies between about 10 μK and 10 mK for typical power sensors |9|, so a high-

-sensitivity thermoelectric device is needed to detect them.

Other performances required to the thermoelectric detector are low internal thermal conductance to avoid significant thermal perturbations on the measurand and high linearity over the power working range of the calorimetric system to have a negligible measurement error on effective efficiency |4|.

Thin-film thermopiles, especially of the T-type meet these requirements and could improve the performance of microcalorimeter by replacing the traditional thermopile with bulky junctions.

System description

A microcalorimeter may be described by the simple thermodynamical scheme of Fig. 2. Inside a thermally insulating container C there is the thermal load L, the bolometer mount under test, which is HF-power and DC-power supplied by means of the transmission lines 1,2. A thermopile detects the temperature difference between the thermal load L and a thermal reference mass M continuously. Line 3 is a thermal transmission line representing the thermal bridges between system components and external environment, and line 4 is the transmission line for the measurement signals, coming from the thermopile and other auxiliary detectors. Lines 1,2,4 have both thermal and electrical impedance, while line 3 exhibits only a thermal impedance.

The system is not adiabatic, but a thermal equilibrium condition exists when the incoming thermal fluxes $\emptyset_1$, $\emptyset_2$, $\emptyset_3$, $\emptyset_4$ are equal to the corresponding outgoing fluxes on the transmission lines 1,2,3,4. At the equilibrium the thermopile response does never change if the bolometer, which measures

HF-power by DC substitution method in virtue of the equivalence of thermal effects, is ideal |1|.

The bolometer is biased at a DC-power level by a self-balancing current loop, Fig. 3, and as HF-power is supplied in addition to it, DC-power is withdrawn, so that the total dissipated energy in the system is constant.

But real bolometers have losses whose effects are to increase the temperature difference ΔT between L and M components. This variation appears on thermopile output and is demonstrated to be a measure of the effective efficiency of the bolometer under test |2|.

A calorimeter may have the same description because the only difference is in the thermal load which is thermally and electrically known.

Thin-film thermopile use

Usually in the calorimeter systems previously described are used thermal detectors having E-type or K-type or T-type bulky junctions.

The necessity to have high thermoelectric power, high linearity, low electrical internal resistance at the typical working temperature of the systems (296 K), imposes the mentioned termocouple types and the T-type better meets all technical requirements.

Numerical values of thermopile parameters depend on the system realization, of course, and in Fig. 4 there is an experimental data collection concerning a particular T-type thermopile used in an IEN microcalorimeter. This thermopile has 90 thermojunctions realized on a continuous constantan wire partially copper plated |10|.

The data are obtained by the experimental set up represented in the block diagram of Fig. 5, suitable to characterize every thermopile type in the range 283 K to 343 K. Inside the microcalorimeter, which has a long term stability of 0.0005 K/day, on the thermopile poles there are two platinum thermometers externally connected to DMM's to measure the thermal drop ΔT between the poles, while the thermopile output E is read by a digital true nanovoltmeter. The usual thermal load, bolometer, is substituted with a resistive load supplied by a calibrated DC-source.

Under computer control for each DC-power level supplied to the thermal load, ΔT and E are read, with the system in stationary condition. From the experimental data are calculated the parameters of the thermopile under test, that is: thermoelectric power $\alpha = 25.3$ µV/K internal thermal conductance c = 0.065 W/K (measured in vacuum), relative nonlinearity NL = 0.076%.

The responsivity r of this thermopile defined as the ratio α/c is 0.389 mV/W, good enough for the particular use of the microcalorimeter. However the performances of this system may be improved with the substitution of the thermal detector.

A thin-film T-type thermopile with 720 copper constantan thermojunctions was realized on a 100 µm thick Kapton-substrate by sputtering and photolithography techniques. The evaluation of this thermopile using the same experimental setup of Fig. 5 leads to a responsivity r = 0.741 mV/W which is due to a thermoelectric power $\alpha = 40$ µV/K and an internal thermal conductance c = 54 mW/K. The thermoelectric power approaches that of a typical copper-constantan thermocouple, while in the former thermopile considered the value of 25.3 μV/K is due to electrical reasons explained in |10|.

The theoretical thermal conductance of the thermopile on Kapton substrate should be 0.350 mW/K and so the responsivity be much higher than the declared value. In practice there are inevitable thermal bridges in the system that increase c to the real value of 54 mW/K.

Another important parameter, improved using the thin-film thermopile, is the signal to noise ratio S/N.

In the microcalorimeter the thermopile works as a voltage generator and the electrical noise is due mainly to the Johnson noise $J = \sqrt{4KT\Delta fR}$ where K is the Stephan-Boltzmann constant, T the absolute temperature at which the thermopile operates, Δf the noise bandwidth of the instrument that reads the thermopile output and R the internal electrical thermopile resistance.

As the internal resistance of the two thermopiles is 220 Ω an 4kΩ respectively, using the real output signals the S/N is 8.54×10^5 for the original thermopile and 1.26×10^6 for the thin-film thermopile with a gain of about 3.5 dB.

Conclusion

The reported experimental results are not the best obtainable, but only a demonstration that the performances of a class of scientific instruments, microcalorimeters and also calorimeters, may be improved acting on the thermoelectric sensor. The use of a thin-film thermopile in an IEN microcalorimeter has produced a gain in responsivity and in signal to noise ratio, without reduction in linearity. However, an order of magnitude may be gained on these parameters if the density of the thermojunctions is increased, the internal electrical resistance reduced as well as the thermal parasitic conductances.

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Appendix A

In its working range a thermopile has an output given by a polynomial expression in T

$$E = n(a_1\Delta T + a_2\Delta T^2 + a_3\Delta T^3 + \ldots)$$

where n is the number of thermojunctions, a_i coefficients depending on thermojunction type and experimentally obtainable. If the expression $na_1\Delta T$ represents the output of an ideal thermopile, may be defined as "relative nonlinearity"

$$NL = \frac{a_2\ \Delta T}{a_1}$$

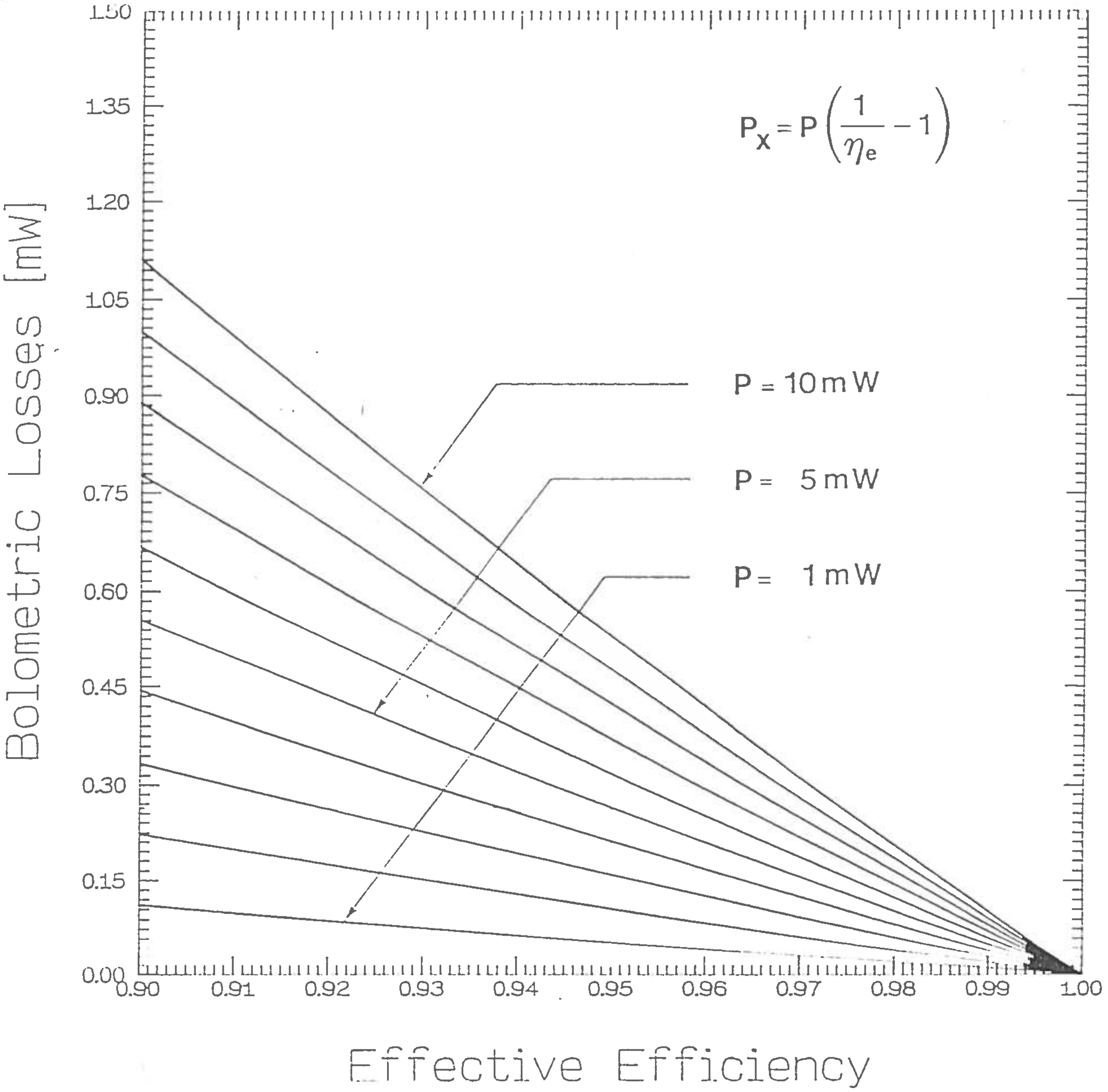

Fig. 1 - Bolometric losses trend P_x versus effective efficiency η_e for typical values of HF-power measured by bolometers.

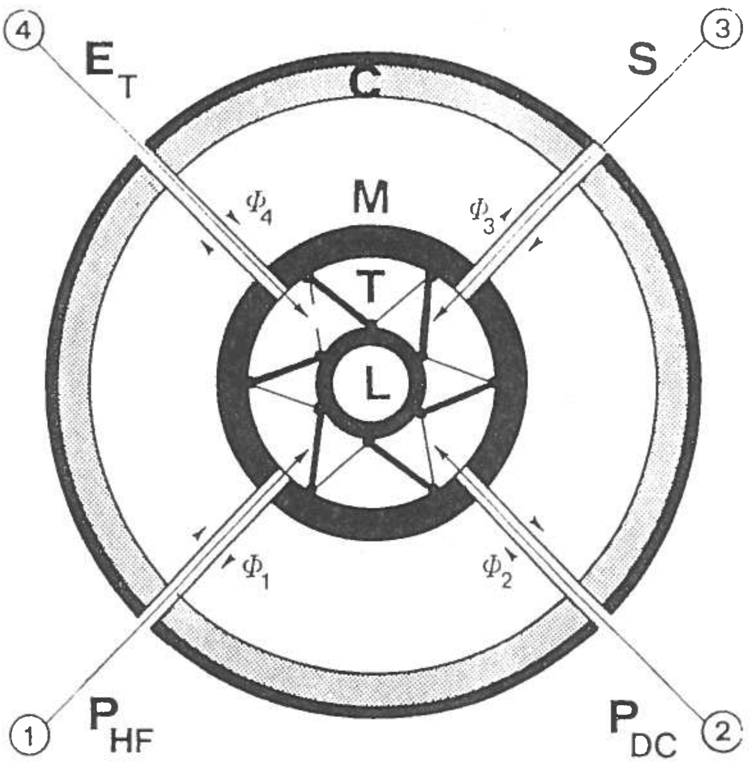

Fig. 2 - Thermodynamical scheme of a microcalorimeter.

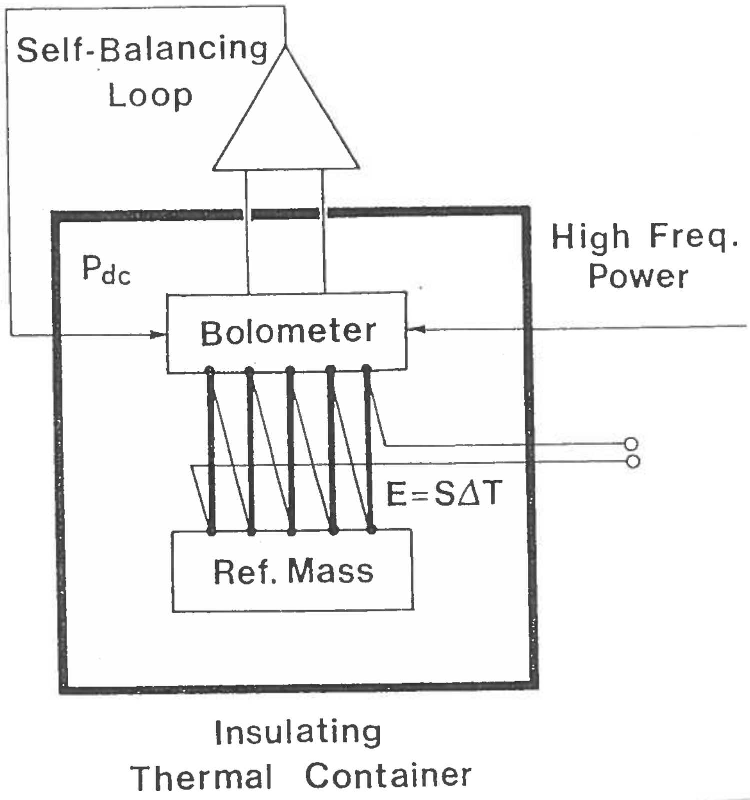

Fig. 3 - Functional scheme of a microcalorimeter.

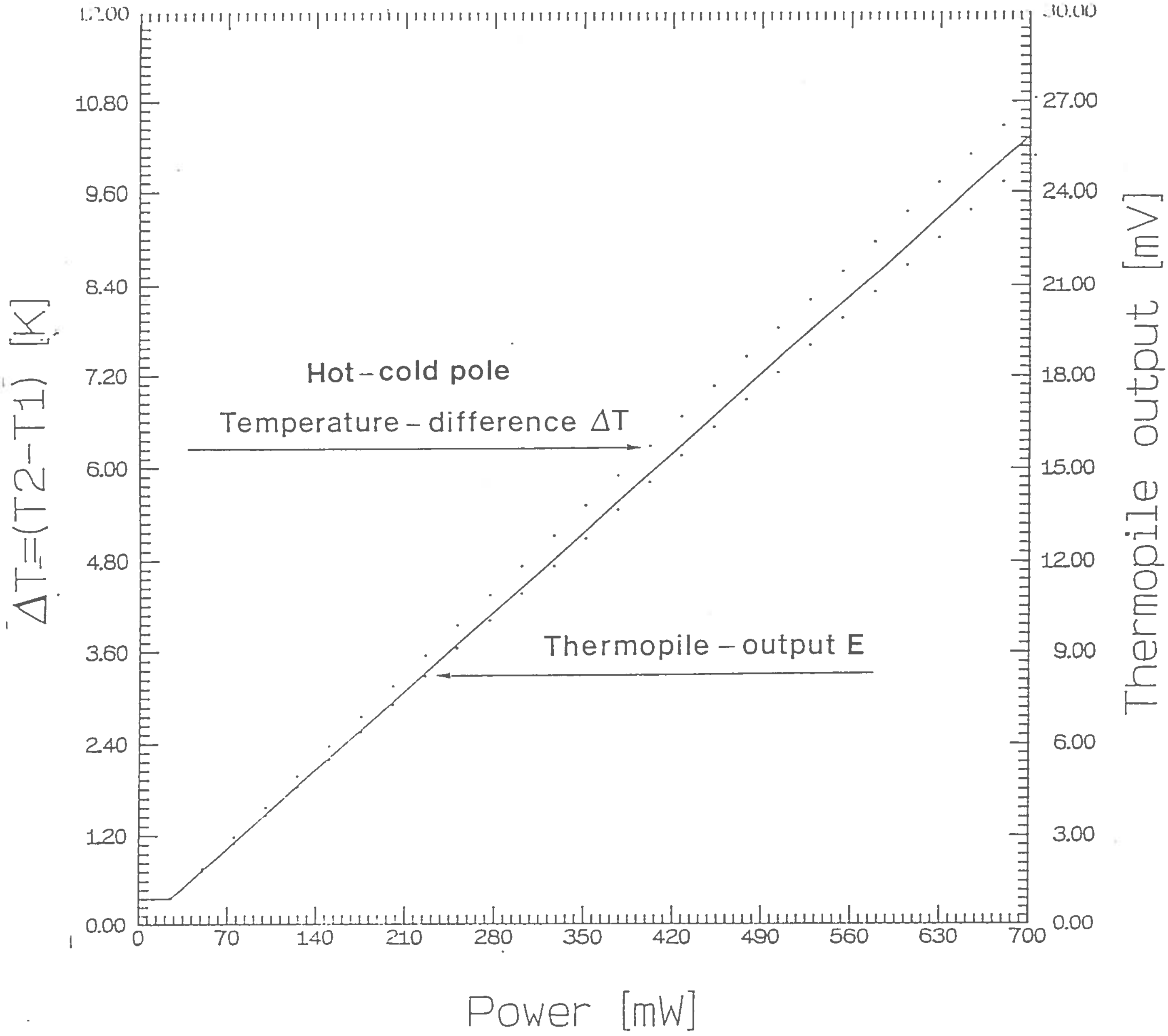

Fig. 4 - Experimental data on a T-type thermopile used in an IEN microcalorimeter.

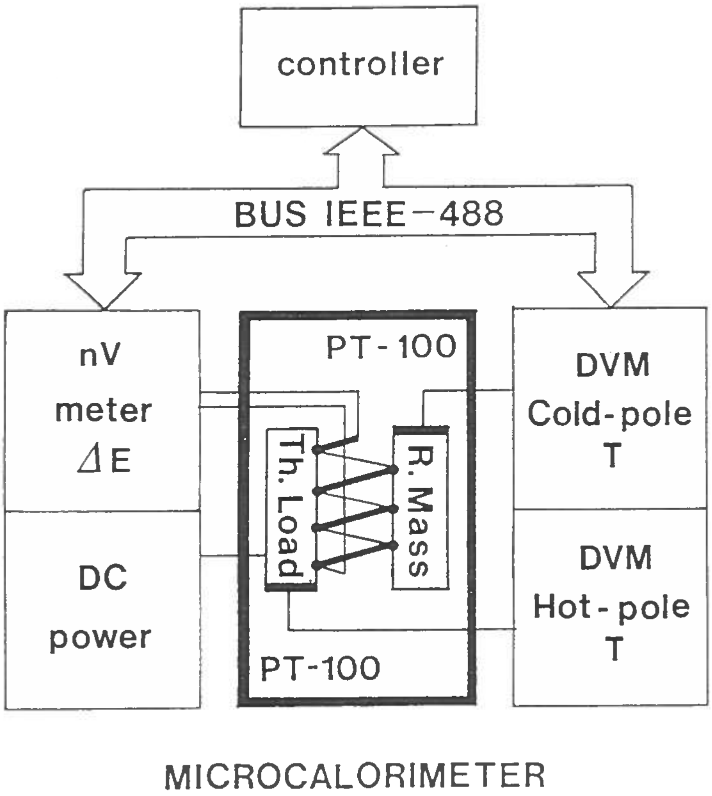

Fig. 5 - Experimental setup for thermopile characterization.