

Novel Thermopile Design for Waveguides and Coaxial Microcalorimeters in the Frequency range from DC – 40 GHz

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Abstract

This work introduces a novel thermopile design for microcalorimeters used in high-frequency microwave power measurements. The thermopile, composed of Copper-Constantan thin-film junctions on an FR4 substrate, enhances sensitivity and accuracy in detecting heat generated when microwave power is applied to a reference power sensor. The new design significantly improves output voltage, leading to better measurement precision. The study focuses on three microcalorimeter setups developed at the Laboratoire National de Métrologie et d'Essais (LNE): a 7 mm coaxial system (APC-7 connector, 10 MHz – 18 GHz) and two waveguide-based systems for K-band (18 – 26.5 GHz) and Ka-band (26.5 – 40 GHz). Experimental results demonstrate that the redesigned thermopile increases voltage output, thereby enhancing sensitivity in microwave power measurements. The Performance comparisons between the new thermopile and the previous design indicate a marked improvement in microcalorimeter efficiency and reliability.

Résumé

Ce travail présente une nouvelle conception de thermopile pour les microcalorimètres utilisés dans la mesure de puissance micro-ondes haute fréquence. La thermopile, constituée de jonctions en film mince Cuivre-Constantan sur un substrat FR4, améliore la sensibilité et la précision dans la détection de la chaleur générée lorsqu'une puissance micro-onde est appliquée à un capteur de puissance de référence. Le nouveau design améliore considérablement la tension de sortie, conduisant à une meilleure précision des mesures. L'étude porte sur trois configurations de microcalorimètres développées au Laboratoire National de Métrologie et d'Essais (LNE) : un système coaxial de 7 mm (connecteur APC-7, 10 MHz – 18 GHz) et deux systèmes à guide d'ondes pour la bande K (18 – 26,5 GHz) et la bande Ka (26,5 – 40 GHz). Les résultats expérimentaux montrent que la thermopile revisitée augmente la tension de sortie, renforçant ainsi la sensibilité des mesures de puissance micro-ondes. Les comparaisons de performances entre la nouvelle thermopile et la précédente indiquent une nette amélioration de l'efficacité et de la fiabilité des microcalorimètres.

1 Introduction

In microwave and millimeter wave applications, there are increasing demands for power measurements [1] – [2]. It is essential for processes, which consist to test the conformity of telecommunication equipment and their proper deployment and use as well. The traceability of microwave power has been obtained using microcalorimeter systems. Since their introduction in 1950s, it is an essential measurement technique for microwave power metrology and continues to be fundamental for most of the National Metrology Institutes (NMIs) as the primary calibration capabilities system for the realization of the primary power standard in microwave frequency [3] – [5]. The traceability of the microwave power is achieved through the measurement of the effective efficiency (η_{eff}) of the reference power standard by the microcalorimeter. The microcalorimeter makes these reference power standard traceable to the direct current (DC) standard, which is SI quantity. The calibrate reference power sensor, which are generally bolometric type sensor in most of NMIs, are then used in direct comparison technique to calibrate microwave power sensor or some microwave power meter. To understand or introduce the role of the thermopile in microcalorimeter measurements systems, it should be useful to give briefly a summary of the microcalorimeter principle in first place.

For the calibration of the reference microwave power sensors, Figure 1 shows the microcalorimeter schematic design that are widespread use as primary microwave power standard. It include the feeding path line that connect the microwave source and DC source to the reference microwave power sensor, a dummy path line that is connected to the dummy microwave power sensor, the thermal insulation line, thermostatic water bath, thermopile and so on. The feeding path line is used for the injection of microwave power, DC or lower frequency signal. The

dummy path is used for temperature reference, no signal is injected. The thermal insulation line helped to reduce the thermal transfer on the feeding line of the calorimeter. The thermostatic water bath maintain the thermal stability of the temperature from outside thermal fluctuation. The effective efficiency of the microwave reference power sensor is determine by using a substitution method which consist of measuring the temperature rise in the calorimeter when it is alternatively supplied with RF power and a reference power (DC or at lower frequency signal 1 KHz for instance). It measure the degree of power transference to the power sensor under calibration when HF frequency power is applied or not. It is define as shown in equation below:

$$\eta_{eff} = \frac{P_{DC\ sub}}{P_{RF\ abs}} \quad (1)$$

Where $P_{DC\ sub}$ is the substituted DC power (or bolometric power) and $P_{RF\ abs}$ is the totale microwave power in the power sensor.

For more details regarding the microcalorimeter, principle is beyond the scope of this study. Therefore, for more specifics, on can refers to these references [6] – [8].

The thermopile primary function in a calorimeter is to detect and measure the heat generated by the microwave power sensor. When microwave power is applied in the power sensor, a parasite thermal loss appear in the microcalorimeter. These losses can be sometimes very low, at the μW level. Therefore, it is crucial to have a very highly sensitive thermopile device to detect them. The purpose of this paper is to replace the thermopile used for microcalorimeter in the frequency range from 10 MHz to 40 GHz that are very bulky with limited number of thermocouple junctions with new thermopile in thin-film to enhance the sensitivity. For the validation of the new thermopile being introduced in the microcalorimeter by comparing the performance data of microcalorimeter with the case of suing the old design of thermopile and the declared CMCs by LNE.

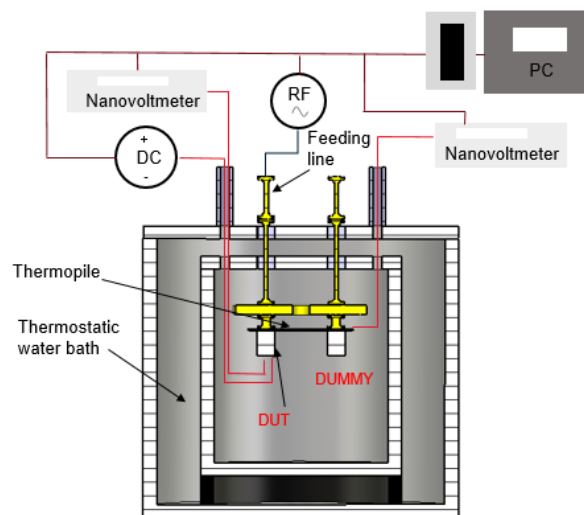


Figure 1: Microcalorimeter set up

2 Microcalorimeter systems description

For this study, three set of microcalorimeters have been used and constructed by Laboratoire National de Metrologie et d'Essais (LNE). One set is a 7 mm coaxial microcalorimeters covering frequency range of 10 MHz – 18 GHz and having an APC-7 connector. Two sets are K Band IEC-R220 (18 – 26.5 GHz) and Ka Band IEC-R320 (26.5 – 40 GHz) waveguide microcalorimeters. The calorimeters are identified as of Joule twin type. The microcalorimeters systems set-up are specifically design for measurement of the effective efficiency of the bolometer mounts type of power sensor. The components of the microcalorimeters are shown in figure 1 and describe schematically in figure 2.

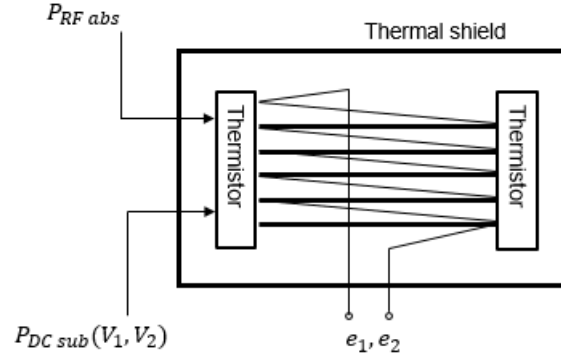


Figure 2: Schematic description of the microcalorimeter

As previously noted, in figure 1 and figure 2, the microwave power standard are two bolometer mount assembled into two symmetrical feeding path. The power measurement of the bolometer mount by microcalorimeter method consist of the measurement of the amount of RF power being transfer to the bolometer element (thermistor). This is done through the measurement of the total heat absorbed by the thermistor when RF power is applied or when it is not applied. The resistance of the thermistor in the feeding path line is keep at a constant value by a self-balancing dc bridge during the measurement process. When the RF power is off and the thermistor is dc-biased by self-balancing dc bridge as shown in figure 2, the dc power dissipation is given by formula below:

$$\frac{V_1^2}{R} = \frac{e_1}{k_1} \quad (2)$$

Where V_1 is self-balancing bridge voltage when RF power is off, R is the operating resistance (in ohms) of the thermistor, e_1 is the output voltage of the thermopile corresponding to V_1 and k_1 (in $V \cdot W^{-1}$) is the sensitivity of the thermopile to power dissipation at the thermistor.

When RF power is applied, the self-balancing bridge reduce the dc power by an amount equivalent to the RF power applied to keep the thermistor operating resistance unchanged and equal to R . the total power dissipated (P_{tot}) in the thermistor is given by equation below :

$$P_{tot} = gP_{RF abs} + \frac{V_2^2}{R} = \frac{e_2}{k_2} \quad (3)$$

Where g is a frequency dependent correction factor for microcalorimeter and bolometer mount combination, when we integrated the RF power loss in the bolometer mount and microcalorimeter feeding transmission line. V_2 is self-balancing bridge voltage when RF power is applied. e_2 is the output voltage of the thermopile corresponding to V_2 . k_2 (in $V \cdot W^{-1}$) is the sensitivity of the thermopile to power dissipation when bolometer mount is dc-bias and RF energized at the same time. For this study, we assume the thermopile response for all three microcalorimeter are linear, therefore, factors k_1 and k_2 are equal ($k_1 \approx k_2$).

As shown in equation (1) for the calculation of the effective efficiency, the substituted dc power $P_{DC sub}$ can be expressed by equation below:

$$P_{DC sub} = \frac{V_1^2 - V_2^2}{R} \quad (4)$$

The substituted dc power by equivalence, correspond to the net RF power absorbed in the thermistor. It is always less than the RF power applied in the bolometer mount.

By combining equations (1) to (4) above, the effective efficiency of the power sensor can be expressed as function of bias voltage and the output thermopile voltage:

$$\eta_{eff} = g \frac{1}{1 + \frac{e_2 - e_1}{e_1} \frac{V_1^2}{V_1^2 - V_2^2}} \quad (5)$$

The accurate measurement of the effective efficiency depends on the determination of g . As noted previously, the totality of RF power applied is not absorbed by the thermistor since we have RF loss in the thermal isolation section waveguide in front of the bolometer mount. Therefore, the RF power dissipated in the thermistor is less than the RF power applied in the microcalorimeter ($P_{RF\ abs}$) and the determination of g correct this source of measurement errors. The detail calculation and the expression of the correction factor g is given by [9] :

$$g = 1 + 0.115 A_{dB} \quad (6)$$

Where A_{dB} is measured insertion loss of the thermal isolation section waveguide in front of the bolometer mount. Therefore, the determination of g is done by using a vector network analyzer (VNA) to estimate the power dissipation in the thermal isolation section waveguide of the microcalorimeter.

3 Thermopile design and use as a power detector

The thermopile is an essential component in the microcalorimeter set up for measuring the RF power dissipated in the system. To achieve accurate RF power measurements with high sensitivity and stability, the thermopile design must meet these requirements by detecting small changes in temperature differences between the active thermistor and the reference thermistor in the system when RF power and DC power are applied. For 7 mm coaxial microcalorimeter in APC-7 connector, the thermopile design has 70 pairs of Copper-Constantan thermocouples connected in series, which were realized on 400 μm RF4 substrate. For waveguide microcalorimeter in K Band and Ka Band, thermopile design have respectively 38 and 26 pairs of Copper-Constantan thermocouples connected in series and realized on top 400 μm RF4 substrate as well. In each set of microcalorimeter, the number of thermocouple was maximized by realizing a two layers type of thermopile with Copper in one side of the FR4 substrate and Constantan in the other side. Both side of the FR4 substrate are connect with vias as junctions, when compare to the former thermopile design where all the thermocouples are realized on top of the substrate. Another advantage of the two layers design is to bring the thermocouples junction much more closer to the RF path of the active thermistor as shown in figure 3.

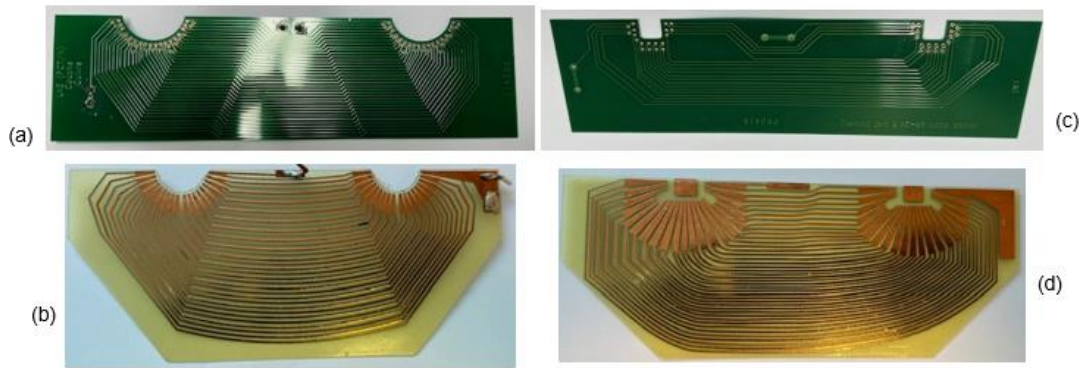


Figure 3: Pictures of the thermopiles. (a) 7 mm coaxial microcalorimeter new design. (b) 7 mm coaxial microcalorimeter former design. (c) Waveguide microcalorimeter K Band new design. (D) Waveguide microcalorimeter K Band former design.

Detail assembly of thermopile assembly in microcalorimeter is shown in figure 4. Two dielectric support are used on top and at the bottom of the thermopile to allow and to keep thermal contact with the active thermistor and thermistor used a reference. This is crucial for the measurement of the temperature rise that occur on the active thermistor when RF or DC power is applied with respect to the temperature of thermistor reference.

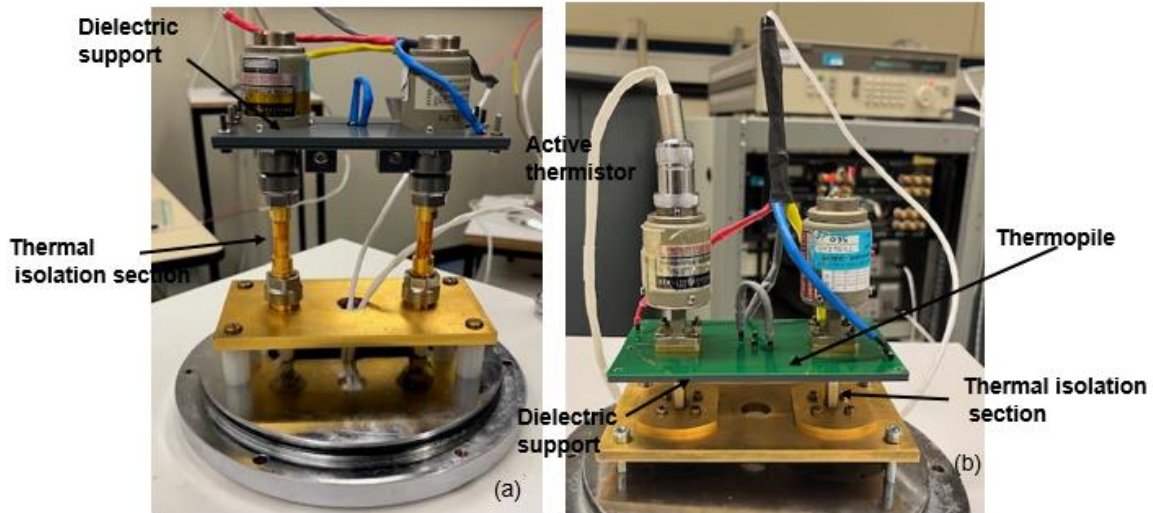


Figure 4: Pictures of the microcalorimeter head. (a) 7 mm coaxial microcalorimeter. (b) Waveguide microcalorimeter K Band.

Figure 5 and Figure 6 shows the thermopile output voltage of each microcalorimeter for three frequencies point and for 10 mW power substitution in DC. For the 7 mm coaxial microcalorimeter, the output voltage for the new thermopile is between 1.151 mV to 1.169 mV, which is more than three time higher than the former thermopile output voltage (0.3330 mV to 0.340 mV). Moreover, for the same substituted power, the results achieve regarding the thermopile output voltage () are higher than those reported by Kwon and all [10] (0.665 mV to 0.680 mV) and by Clague [11] (0.109 mV to 0.112 mV). K Band IEC-R220 (18 – 26.5 GHz) waveguide microcalorimeter, the output voltage vs time measured is between 0.267 mV to 0.272 mV for the new thermopile design and between 0.133 mV to 0.135 mV for the old version. Regarding the Ka Band IEC-R320 (26.5 – 40 GHz) waveguide microcalorimeters, the results show an output voltage between 0.226 to 0.233 mV, which is two time higher than those measured with former thermopile version (0.165 mV to 0.171 mV). Therefore, the new thermopile design response largely increase measurement sensitivity when compare to the former thermopile design.

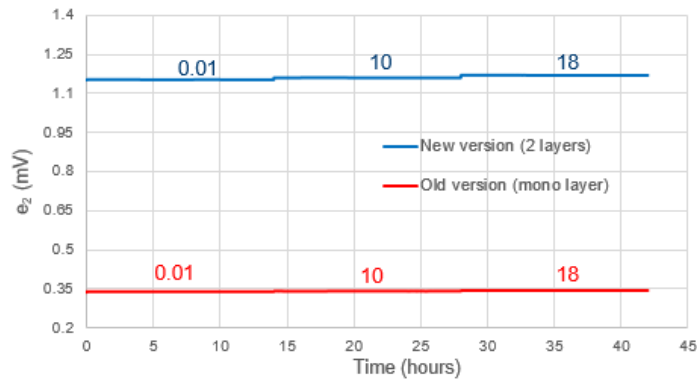


Figure 5: Thermopile output voltage versus time acquisitions for three frequencies (GHz). 7 mm coaxial microcalorimeter in APC7 connector.

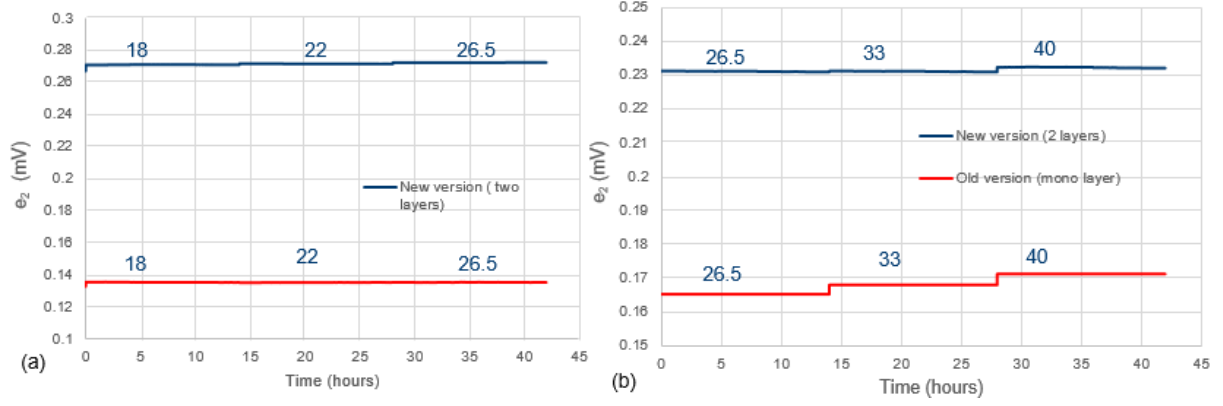


Figure 6: Thermopile output voltage versus time acquisitions for three frequencies (GHz). (a) Waveguide microcalorimeter k Band. (b) Waveguide microcalorimeter Ka Band.

When designing the thermopile, a key critical parameter one should consider is the internal electrical resistance. In the microcalorimeter systems, thermopile can be describe as voltage signal generator and the electrical noise depends mainly to the Johnson noise, which is given by formula below:

$$V_{noise} = \sqrt{4 k_B T_e B R_{th}} \quad (7)$$

Where k_B is the Boltzmann constant, T_e is the external temperature at which the thermopile operates, B is the noise bandwidth of the instrument that read the thermopile output voltage and R_{th} is the thermopile internal electrical resistance.

Typically, for the 7 mm coaxial microcalorimeter in APC7, R_{th} value of the new thermopile and the former one are respectively 546.5 Ω and 98 Ω . Therefore the Signal-To-Noise Ratio (SNR) are 1.48×10^{10} and 7.22×10^9 for the new thermopile and the former respectively. That led to a gain of around 6 dB. Regarding the waveguide microcalorimeter in K Band, R_{th} are 150 Ω and 320 Ω for the former thermopile and the new version respectively. This provide a gain of about 5 dB when comparing the signal output voltage. In the case of the waveguide microcalorimeter Ka Band, the resulting gain result between the two thermopiles design can be expressed approximatively 1.3 dB.

4 Effective efficiency results and comparison

For the validation and comparison, we characterized in the microcalorimeter thermistor mounts that were used as transfer standard. The results are shown in Table 1.

For the 7 mm coaxial, K band waveguide and the Ka band waveguide thermistor mounts, the results show good agreements within the assigned uncertainties ($\Delta\eta_e$) when compared with the declared CMCs values. Regarding the comparison with the two thermopiles, the improvement of the thermopile responsivity slightly improve the microcalorimeter performances as show in figure 7.

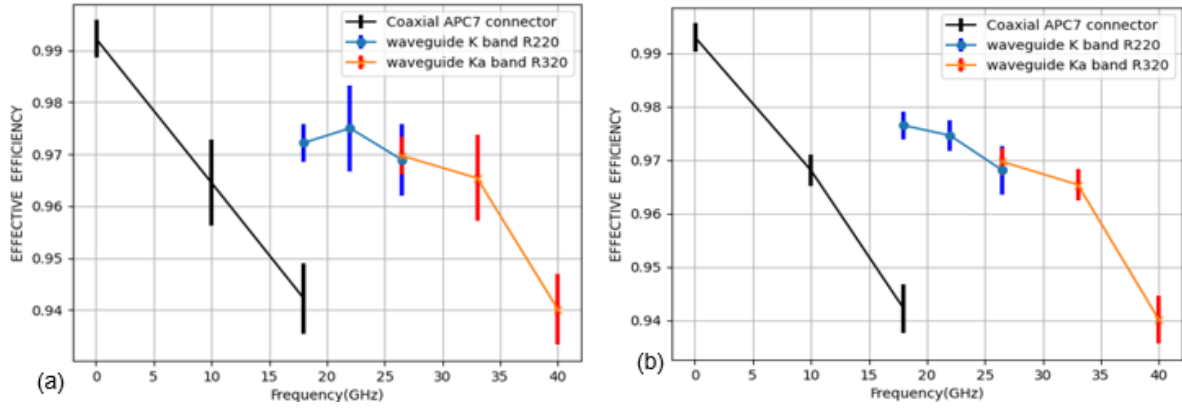


Figure 7: Effective efficiency measurement results. (a) Microcalorimeter with old thermopile design. (b) Microcalorimeter with new thermopile design.

Transfer Standard	Frequency (GHz)	Old thermopile design		New thermopile design		LNE Expanded Uncertainty CMC
		η_e	$\Delta\eta_e$	η_e	$\Delta\eta_e$	
HP 8478B APC-7	0.01	0.9922	0.0036	0.9930	0.0026	0.0026
	10	0.9645	0.0083	0.9681	0.0029	
	18	0.9422	0.0064	0.9422	0.0045	
HP K486A	18	0.9722	0.0064	0.9765	0.005	0.0046
	22	0.9750	0.0061	0.9746	0.0051	
	26.5	0.9689	0.0056	0.9681	0.0048	
HP R486A	26.5	0.9697	0.0087	0.9697	0.008	0.008
	33	0.9654	0.0117	0.9654	0.008	
	40	0.9401	0.0101	0.9401	0.008	

Table 1: Results of the effective efficiency measurement

5 Conclusion

For primary RF power measurement, new design of thermopiles have been developed and evaluated in the coaxial (using APC-7 connector) and waveguide (K band and Ka band) microcalorimeters. The result clearly show a gain in the voltage measurement and responsivity of the thermopile. As a result of this work, the set of thermopile improve our microcalorimeter performances regarding the effective efficiency measurement within the assigned uncertainties level.

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