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Coaxial microcalorimeter – National standard for microwave power up to 18 GHz at NPLI

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National Physical Laboratory India (NPLI) is the premier research and development centre and the National Metrology Institute (NMI), which provides apex level calibration services to the country. The coaxial microcalorimeter is used for assigning the effective efficiency of the reference standard coaxial thermistor mount in the frequency range 10 MHz-18 GHz. Measurement technique for calibrating microwave power reference standard has been presented. The calibration results and the various factors influencing the results have been explained. All the measurements are performed using a fully automated data acquisition system, which has been developed indigenously in the laboratory. The uncertainty components in assigning the effective efficiency using calorimeter system have been discussed. The calibration uncertainty, which is a function of frequency ranges from 0.2 per cent at 10 MHz to 0.7 per cent at 18 GHz.

Keywords: Coaxial microcalorimeter, *RF* power standard, Coaxial thermistor mount, Correction factors, Effective efficiency, Uncertainty

1 Introduction

Coaxial microcalorimeter and an associated reference standard are being used as the national standard of microwave power in various national metrology institutes (NMIs) of the world. With the establishment of coaxial microcalorimeter system, one can calibrate the thermistor mounts directly with the improved uncertainties. In the microcalorimeter system, the total microwave power dissipated in the thermistor mount and the *dc*-substituted power are measured simultaneously to determine the effective efficiency of the thermistor mount[1-4]. This is the key technique for the realization of microwave power national standard and its traceability is obtained by assigning the effective efficiency of thermistor mounts as a function of frequency. This paper presents the technique for calibrating a coaxial thermistor mount using coaxial microcalorimeter system in the frequency range 10 MHz-18 GHz along with its correction factors influencing the measured effective efficiency.

2 Measurement Technique

The NPLI microwave power standard consists of both a coaxial microcalorimeter and an associated thermistor mount. In the bolometric measurement of microwave power, a major part of the power going into the thermistor mount from the synthesized source is absorbed in the element and a small part of the power gets absorbed in the body of the mount. This part of power has to be determined through microcalorimeter system in terms of rise in temperature of the thermistor mount to determine the effective efficiency[2,3] which is defined as the ratio of the substituted *dc* power divided by the total microwave power dissipated in the mount and is calculated using Eq. (1):

$$\eta_e = \frac{P_b}{P_{RF}} \qquad \ldots(1)$$

where P_b is the *dc* substituted power and P_{RF} is the total *RF* power dissipated in the mount.

The coaxial thermistor mount has been biased using self-balancing bridge (SBB) to an operating resistance which produces a nominal match to the characteristic impedance of the transmission line. The mount which is connected in one of the arms of the SBB maintains the *dc* resistances of the thermistor mount at a constant value of 200 ohms. As soon as the microwave signal is fed in, the bridge reduces the *dc* power by an amount almost equal to the microwave power entering in the mount. This is called substitution technique as microwave power replaces a portion of *dc* biased power. The substituted *dc* power (P_b) is calculated using the Eq. (2). The detailed derivation of the equation is available in Ref. (3).

$$P_b = P_1 - P_2 = \frac{v_1^2 - v_2^2}{R_0} \qquad \ldots(2)$$

where P_1 is the *dc* biased power, v_1 is the *dc* voltage across the mount with no *RF, P_2* is the *dc* biased power, v_2 is the *dc* voltage across the mount with *RF* and R_0 is the *dc* operating resistance of the thermistor mount.

To determine the effective efficiency of an unknown thermistor mount, it is connected in the active transmission line of the microcalorimeter where biasing voltage and microwave signal is applied and the other thermistor mount is connected in the reference line of the system. Active side thermistor mount biasing leads are connected to the self-balancing bridge whose voltage output (v) has been recorded using digital voltmeter. The microcalorimeter measures P_{RF} by measuring the temperature rise of the active thermistor mount in reference to passive one using thermopile assembly. A coaxial microcalorimeter measurement system is shown in Fig. 1 along with the coaxial thermistor mounts which is shown in Fig. 2.

The cross-sectional view of the coaxial microcalorimeter is shown in Fig. 3. As shown in Fig. 3 two input lines are shown having same N type connector coupling 'A' and either of the two lines can be used as the active side to which the thermistor mount to be calibrated is attached and the other line serves as the thermal reference side. In order to prevent conduction of the heat flow in either direction, three specially fabricated isolation sections 'B' have been incorporated. Each isolation section is fabricated from low thermal conductivity perspex material which has a thin coating of copper and gold with highly polished surfaces[4,5]. An internal view of the coaxial microcalorimeter system is shown in Fig. 4. To monitor the temperature difference between the active and the reference thermistor mount, a

Fig. 1 — Coaxial microcalorimeter measurement system

Fig. 2 — Coaxial thermistor mounts

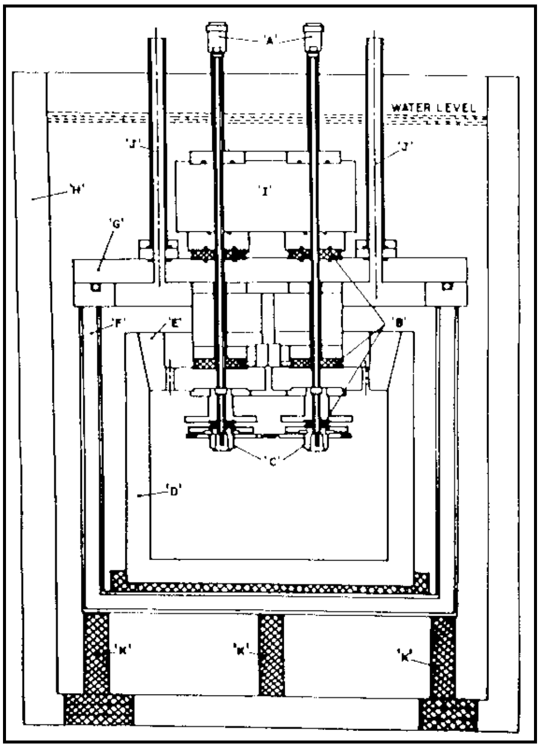


Fig. 3 — Cross-section of the coaxial microcalorimeter

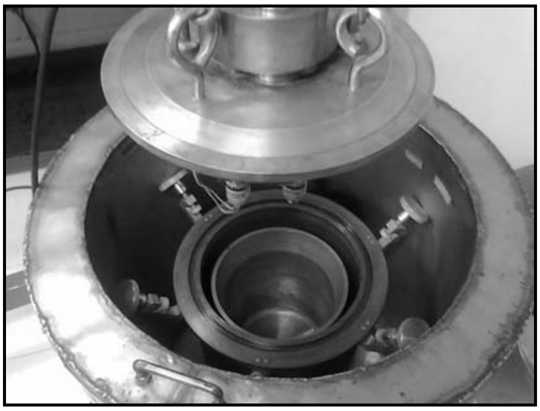


Fig. 4 — Internal view of the coaxial microcalorimeter system

thermopile having 44 junctions of NiCr-constantan thermocouple on each side has been fixed on the flange to which thermistor mounts are coupled. The thermopile is very sensitive and it gives a thermo emf output in μV corresponding to the temperature difference, when *RF* power is applied to the thermistor mount. Thermopile output voltage (*e*) is measured from digital nanovoltmeter. Both DMM and nanovoltmeter are interfaced to the computer. By using Eq. (3) effective efficiency[3] is determined.

$$\eta_e = g\eta_e' = g\left[\frac{1-(v_2/v_1)^2}{(e_2/e_1)-(v_2/v_1)^2}\right] \quad \ldots(3)$$

where g is frequency dependent correction factor, η_e' the effective efficiency without correction. v_1, v_2 the SBB voltage for *RF* power OFF and ON conditions,respectively and e_1, e_2 are the thermopile voltage corresponding to v_1, v_2, respectively at steady condition.

2.1 Correction factors

There are three major factors that influence the measured effective efficiency of the reference standard thermistor mount due to the design of the microcalorimeter. The method of correction factor analysis is taken from Ref. (2). These are *RF* loss in the thermal isolation section of the calorimeter (L), *RF* loss in the wall of the reference standard thermistor mount (A) and non-linear thermopile response of the calorimeter (Q). These parameters L, A and Q are determined by the Eqs (4-6), respectively. All these corrections combine to give the total correction factor (g), which is determined by Eq. (7).

The *RF* loss in the thermal isolation section and the input lead in front of the input to the thermistor mount under calibration causes an additional thermopile emf e_L. The correction factor L for η_e' is given by Eq. (4):

$$L = 1 + \left[\frac{e_L / e_1}{(e_2/e_1)-(v_2/v_1)^2}\right] \quad \ldots(4)$$

where *RF* loss causes an additional thermopile emf as e_L, which is estimated as $0.8\sqrt{f/18}$, f is frequency of operation. The uncertainty of the additional emf e_L is assigned as $e_L/2$ and that of the factor L becomes $(L-1)/2$.

The thermopile response for the *RF* power absorbed in the thermistor mount is dependent on the position of the regions where absorption occurs. The correction factor A for η_e' is given by Eq. (5):

$$A = 1 + (1-\eta_e') \times W \quad \ldots(5)$$

where W is the local heating effect difference of coaxial thermistor mount. A figure of 2 per cent is arbitrarily assigned to this effect. The uncertainty of this factor is $(A-1)$.

The relation between power dissipated within the thermistor mount and the thermopile emf e is not exactly linear. By changing a small amount of *dc* power fed in to the thermistor mount, non linearity has been obtained as a function of Δe by experiments. The correction factor Q for η_e' is given by Eq. (6):

$$Q = 1 - x\left[\frac{1}{p(2-p)}\right] \quad \ldots(6)$$

where $x = (0.001/14)\,\Delta e$, $\Delta e = e_2 - e_1$ and $p = (v_1 - v_2)/v_1$

The uncertainty of this factor is $(1 - Q)$. The total correction factor 'g' is given by the Eq. (7):

$$g = LAQ \quad \ldots(7)$$

The value of the correction factor 'g' for the coaxial thermistor mounts ranges from 1.000 to 1.008 depending upon the frequency and the type of the thermistor mount used. The total uncertainty in measuring effective efficiency of the reference standard thermistor mount is about 0.2 to 0.7 per cent. Detailed descriptions of the principle of microcalorimeter are available in Refs (2, 6).

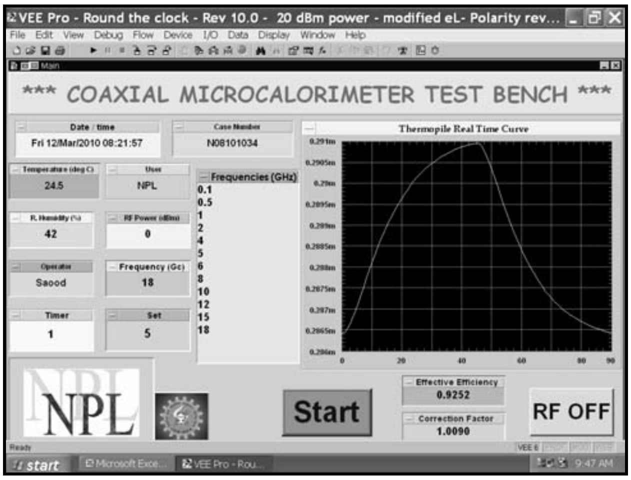
2.2 Automated measurements

Instrumentation is one of the major areas of Science and Technology, which makes a great impact on vital sectors of national activities. Software for Coaxial microcalorimeter system is developed indigenously using the VEE Pro application, which is a graphical programming environment optimized for use with electronic instruments. Measurements are required at a number of frequencies and each measurement per frequency requires data acquisition from the digital voltmeter and the nanovoltmeter continuously for eight hours after every sixty seconds and, since the calorimeter is intrinsically slow in coming to equilibrium, automation is almost a necessity.

The program enables the computer to continuously acquire the raw data from the electronic equipments, display it as a graph in a real time environment and save it in a tabular form. The front panel view and the back panel view of the software are shown in Figs 5 and 6, respectively[1,5]. Developing this system minimizes human involvement and therefore reduces the chances of errors. It eliminates the need to record the reading manually or perform any cryptic and error-prone steps like preprocessing, compiling, or linking to run the software. The automated measurement results along with its expanded uncertainty have been shown in Table 1. Automation transforms a slow and costly task into a quick and accurate procedure.

3 Measurement Results

Measurement was performed to measure the effective efficiency and reflection coefficient of a coaxial thermistor mounts in the frequency range 10 MHz-18 GHz along with its expanded uncertainty having a coverage factor (*k*=2). The calibration results of coaxial thermistor mounts (Agilent 478A and 8478B) using coaxial microcalorimeter along with the reflection coefficient are shown in Table 1. The plot showing the effective efficiency along with the uncertainty bars is shown in Fig. 7. The reflection coefficient is considered to be an auxiliary parameter, mainly needed to determine the mismatch uncertainty i.e. a mismatch between *RF* signal source and the thermistor mount under calibration.



*** COAXIAL MICROCALORIMETER TEST BENCH ***

Date / time: Fri 12/Mar/2010 08:21:57

Case Number: N08101034

Temperature (deg C): 24.5

User: NPL

R. Humidity (%): 42

RF Power (dBm): 0

Operator: Saood

Frequency (Gc): 18

Timer: 1

Set: 5

Frequencies (GHz): 0.1 0.5 1 2 4 5 6 8 10 12 15 18

Effective Efficiency: 0.9252

Correction Factor: 1.0090

Fig. 5 — Front panel view of the Microcalorimeter software

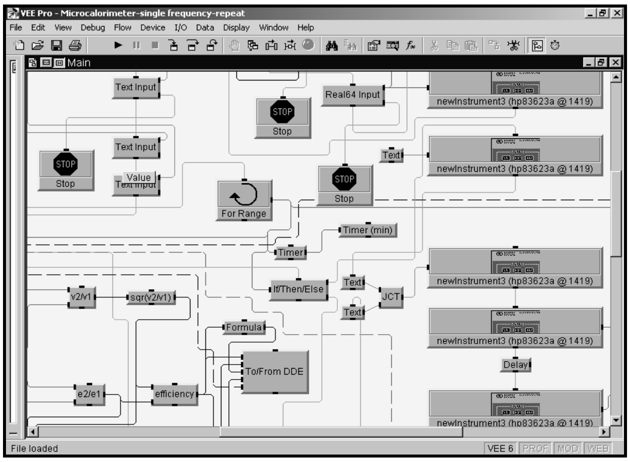


Fig. 6 — Back panel view of the Microcalorimeter software

3.1 Microcalorimeter uncertainty

The uncertainty in determining the effective efficiency using coaxial microcalorimeter depends upon the uncertainty in the correction factor '*g*' and the instrumentation uncertainty, which consists of uncertainty in measuring the biasing voltages of the reference standard thermistor mount using SBB and digital voltmeter (DVM) and uncertainty in measuring the thermopile emf using nano voltmeter. An

Table 1 — Effective efficiency and reflection coefficient with uncertainty

Frequency GHz	Effective efficiency	Expanded uncertainty	Reflection coefficient	Expanded uncertainty
0.01	0.9979	0.0020	0.0147	0.0150
0.05	0.9975	0.0020	0.0147	0.0150
0.10	0.9972	0.0017	0.0153	0.0150
0.50	0.9937	0.0018	0.0133	0.0150
1.00	0.9894	0.0019	0.0196	0.0150
2.00	0.9847	0.0020	0.0268	0.0150
4.00	0.9782	0.0022	0.0301	0.0150
6.00	0.9710	0.0025	0.0375	0.0200
8.00	0.9649	0.0028	0.0206	0.0200
10.00	0.9598	0.0031	0.0343	0.0200
12.00	0.9527	0.0039	0.0593	0.0200
14.00	0.9480	0.0047	0.0842	0.0200
16.00	0.9396	0.0058	0.1217	0.0200
18.00	0.9258	0.0075	0.1486	0.0200

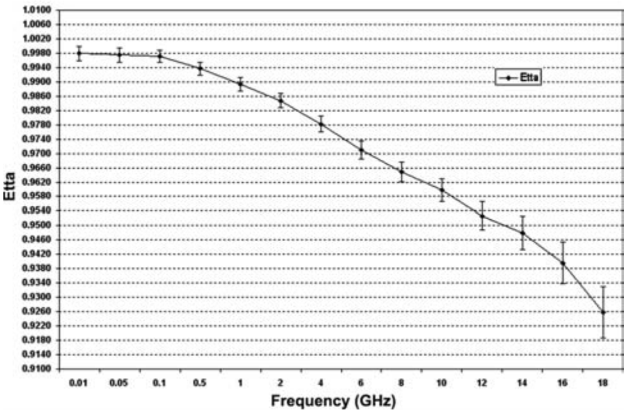


Fig. 7 — Effective efficiency with uncertainty bars

Table 2 — Uncertainty budget for determining the effective efficiency of a thermistor mount using coaxial microcalorimeter

	Uncertainty Budget at 16 GHz						
Source of uncertainty	Estimates (A)	Limits xi (A)	Probability	Standard uncertainty ui (xi) A	Sensitivity coefficient ci	Uncertainty contribution ui (y) A	Degree of freedom (ni)
			Type A/B Factor				
Correction Factor "g"	0	0.0055	Normal Type B	0.002750	1	0.002750	∞
Thermopile Non linearity	0	0.0010	Rectangular Type B	0.000577	1	0.000577	∞
Nano-voltmeter Instability	0	0.0004	Rectangular Type B	0.000231	1	0.000231	∞
DVM Instability	0	0.0007	Rectangular Type B	0.000404	1	0.000404	∞
SBB Instability	0	0.0006	Rectangular Type B	0.000346	1	0.000346	∞
Repeatability			Normal Type A	0.000461		0.000461	4
Combined Standard Uncertainty Uc(η_e)						0.002905	∞
Expanded Uncertainty U(η_e)							2136
			k=2			0.005810	
						0.58	%

uncertainty budget in assigning effective efficiency using coaxial microcalorimeter at 16 GHz is presented in Table 2. In the uncertainty budget analysis, there are three main contribution factors apart from the factors due to specific measurement set-up of an individual laboratory. They are uncertainty in the correction factor, Instrumentation Uncertainty and Repeatability (spread in the measurement data). We have also participated in a bilateral comparison with PTB-Germany in 2008. The comparison result shows that the national standard of NPLI is at par and established a close degree of equivalence with PTB-Germany[7].

4 Conclusions

Coaxial microcalorimeter system forms the basis of national standard of microwave. It is the fundamental method for assigning the effective efficiency to the reference standard thermistor mounts at the desired frequencies. NPLI provides apex level calibration services in microwave power to the country. Automation of the measurement technique and its necessity have been discussed and used for calibrating the reference standard thermistor mounts. The national standard has been successfully evaluated for the effective efficiency using automated system. The calibrated result shows that the effective efficiency ranges from 0.9979 ± 0.0020 at 10 MHz to 0.9258 ± 0.0075 at 18 GHz. The bilateral comparison result shows that we have established a close degree of equivalence of our national standard with the corresponding standards of leading NMIs.

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