Status of Precise RF Power Measurement

Dieter Janik (1) and Jan de Vreede (2)

(1) Physikalisch-Technische Bundesanstalt (**PTB**)**,** Bundesallee 100, 38116 Braunschweig, GERMANY
tel: ++49531 592 2222, fax: : ++49531 592 2228, e-mail: dieter.janik@ptb.de

(2) Van Swinden Laboratory **(NMi VSL)**, P. O. Box 654, 2600 AR Delft, The Netherlands,
tel: ++31 15 269 1500, fax: ++31 15 261 2971 e-mail: jdevreede @nmi.nl

ABSTRACT

Radio frequency (RF) power is one of the most important quantity in RF metrology. In recent years significant progress has been achieved in developing new primary RF power standards with extended frequency ranges and improved uncertainties. These developments and the results of numerous international comparisons in the field of precise RF power measurements carried out in the last years are reviewed in this paper.

RF POWER STANDARS

For most precise and traceable RF power measurements the principle of RF/dc substitution calorimetry [1, 2] is used for primary standards in the frequency range from dc to well above 100 GHz. By comparing the heating effects of the RF power and a substituted dc power in the absorbing element of a calorimeter, the RF power is traced back to a dc power standard. In a practical calorimeter, corrections are usually necessary because of the nonequivalence of the response to identical RF and dc powers. These corrections determine the “effective efficiency”. The effective efficiency of the calorimeter is the ratio of the substituted dc power and the absorbed RF power, both resulting in the same temperature increase in the absorbing element.

The calorimeters used as primary power standards in national metrology institutes (NMIs) are the microcalorimeter type and the dry load calorimeter type. In microcalorimeters the effective efficiency of an inserted bolometer mount, which functions as the calorimeter load, is measured. After calibration, this bolometer mount is used as a secondary standard for power measurements. In the case of dry load calorimeters the calorimeter itself functions as the calorimetric load, and its effective efficiency is determined by measurements and theoretical analysis. Secondary power standards are calibrated by comparing their response with that of the dry load calorimeter using a stable RF generator system.

For many years several NMIs have been equipped with calorimeters for coaxial 7 mm lines up to 18 GHz (PC 7- and N-connector), and for selected waveguide bands between 8,2 GHz and 100 GHz. One of the NMIs offers power calibration services covering the continuous frequency range between 8,2 GHz and 110 GHz traced back to waveguide microcalorimeters [3]. A waveguide dry load calorimeter was described also for higher frequencies of up to 178 GHz [4]. The typical values of the combined uncertainty (k = 2) of the effective efficiency for waveguide bolometer mounts calibrated in microcalorimeters or for dry load calorimeters are about 0,0015 for frequencies up to 10 GHz, about 0,003 up to 40 GHz, increasing to about 0,015 for frequencies between about 100 GHz and 178 GHz.

Due to an increasing need for precise power measurements in new, very broad coaxial line systems, the NMIs have started developing calorimeters for such coaxial line systems. For the PC 3,5 mm line system up to 26,5 GHz a microcalorimeter was described in [5] and a dry load calorimeter in [6]. A complete calibration system with a coaxial calorimeter of the dry load type for the PC 2,9 mm line system up to 40 GHz is described in [7]. Most broadband coaxial calorimeters today are calorimeters for the 2,4 mm line system up to 50 GHz; a dry load calorimeter [8] and a microcalorimeter [9] exist. Typical values of the combined uncertainty (k = 2) for the effective efficiency of bolometer mounts calibrated in coaxial microcalorimeters or for dry calorimeters are approximately 0,004 for coaxial 7 mm lines up to 18 GHz, 0,015 for 3,5 mm lines up to 26,5 GHz, 0,022 for 2,9 mm lines up to 40 GHz and 0,016 for 2,4 mm lines up to 50 GHz. In recent years many NMIs equipped with power measurement traced back to calorimeters of other NMIs began to build up their own microcalorimeter or dry calorimeter in order to become independent. In general, they start with a calorimeter for the 7 mm coaxial line system with N-connectors.

When microcalorimeters are employed as primary power standards, suitable bolometer mounts must be used inside of the microcalorimeter and they are calibrated as secondary standards. The problem with the new coaxial line systems above 18 GHz is that commercial bolometer mounts are available only with 7 mm connectors up to 18 GHz and with 3,5 mm connectors up to 26,5 GHz. It has been shown that instead of a bolometer mount a modified 3,5 mm commercial thermal electric power sensor can be calibrated in a microcalorimeter to serve as a secondary power standard [10]. For the coaxial 2,4 mm microcalorimeter a special thin film bolometric power detector for the 2,4 mm line system was developed [9] .

Since calorimeter measurements are slow and since some detectors are not suitable for microcalorimeter measurements, a broadband direct comparison system with 2,4 mm line connectors for frequencies between 50 MHz and 50 GHz was developed [9]. It is used to calibrate all types of power detectors including 3,5 mm and 2,9 mm with uncertainties traceable to the new thin film bolometric detector and the 2,4 mm microcalorimeter. This coaxial direct comparison system primarily consists of a synthesizer and a two-resistor power splitter. A 2 GHz to 50 GHz amplifier is used to increase the power at the measurement port at the higher frequencies. A monitor detector, P_m , is connected to one side arm (port 3) of the splitter. Measurements of the device under test (DUT) are carried out by alternately connecting the bolometric detector, as a standard detector (P_S), and the DUT (P_{DUT}) to the other side arm of the splitter. The effective efficiency η_{DUT} of the DUT is then given by $\eta_{DUT} = \eta_S \cdot (P_{3,S}/P_{3,DUT}) \cdot (P_{DUT}/P_S) \cdot (M_S/M_{DUT})$, where η_S is the effective efficiency of the standard, $P_{3,S}$ is the dc substituted power at the port 3 monitor detector when the standard is connected, and $P_{3,DUT}$ is the dc substituted power at the port 3 monitor detector when the DUT is connected. P_{DUT} and P_S are the dc substituted power of the DUT and the standard detectors, respectively, and M_{DUT} and M_S are their mismatch factors. The mismatch factors are given by the reflection coefficients of the standard Γ_S and of the DUT Γ_{DUT} by $M_S = (1-|\Gamma_S|^2) / (|1-\Gamma_S\Gamma_G|^2)$ and $M_{DUT} = (1-|\Gamma_{DUT}|^2) / (|1-\Gamma_{DUT}\Gamma_G|^2)$, respectively.

The equivalent source reflection coefficient Γ_G of the power splitter can be expressed by the scattering parameters S_{ij} of the splitter: $\Gamma_G = S_{22} - S_{12} \cdot S_{23} / S_{13}$. A unique technique based on 1-port vector network analyser (VNA) calibration methods has been developed for measuring Γ_G [11]. First, ports 1 and 3 of the power splitter are connected to ports 1 and 2 of an uncalibrated VNA. When a device with known reflection coefficient Γ is connected to port 2 of the splitter, it can be shown that $\Gamma = (S_{11m}/S_{21m} - e_{00})/([S_{11m}/S_{21m}] \cdot \Gamma_G - \Delta_e)$, where S_{11m} and S_{21m} are the measured reflection and transmission parameters of the uncalibrated VNA, and e_{00} and Δ_e are complex constants. Γ_G is determined by connecting three devices with known Γ (i.e. short, open, load) to port 2 of the splitter and solving for Γ_G , e_{00} , and Δ_e . It is important to realize that Γ_G can be determined by measurements of S_{11m} and S_{21m} on an uncalibrated VNA. The procedure outlined essentially calibrates port 2 of the splitter so that it can perform 1-port VNA measurements. However, only the measurement of Γ_G is of interest to the direct comparison system. This measurement technique is fast and yields accuracies typical of those achieved for 1-port VNA calibrations.

The combined uncertainty (k = 2) for measurements of coaxial bolometric detectors as a DUT on the direct comparison system dependents on the detector, but typically ranges from 0,004 at 50 MHz to a maximum of 0,02 at 50 GHz. The uncertainty for measurements on thermocouple detectors is slightly higher.

INTERCOMPARISONS

Most of the radio frequency comparisons between NMIs are organized by the RF working group (GT-RF) of the Comité Consultatif d'Electricité et Magnétisme (CCEM) of the Metre Convention. These so-called key comparisons now provide the technical basis for the Mutual Recognition Arrangement (MRA), by which the national institutes agree on the equivalence of their standards. The guidelines on the new comparisons state clearly that in the final report a "detailed" uncertainty budget of the measurement set-up should be provided by each laboratory.

The GT-RF has organized many comparisons which had already started in the sixties as a continuation of the work initiated by Commission A of URSI. Most radio frequency quantities, such as RF power, attenuation, impedance, noise and voltage have been covered both in coaxial and waveguide transmission lines and in the frequency range from below 1 MHz up to 100 GHz.
In the recent ten years the national metrology institutes have been invited to participate in a number of comparisons in the field of RF and microwave power. Most of these comparisons have started, but of only a few results have been published.

For waveguide transmission lines the comparisons were concerned with the mid-band frequencies of 33 GHz, 45 GHz, 62 GHz, 75 GHz and 94 GHz. In two cases [12, 13] the results have been published. The effective efficiency of thermistor mounts have been determined with an uncertainty (k = 1) of 0,2 % – 0,7 % for 33 GHz and of 0,5 % – 1,0 % for 62 GHz. Only a few national standards laboratories participated in these comparisons.

For coaxial transmission lines the comparisons were concerned with selected frequencies between 10 MHz and 18 GHz using thermistor mounts with APC7- and type-N connectors, and selected frequencies between 50 MHz and 26 GHz using dc-coupled sensors with 3,5 mm connector. In these comparisons many laboratories have been participating. Results of a comparison carried out around 1990 [14] using thermistor mounts with APC7-connectors at frequencies of 12 GHz, 14 GHz and 17 GHz show uncertainties of 0,3 % – 1,0 % using microcalorimeters. The results of a regional comparison [15] show uncertainties (k = 2) of 0,3 % – 2,0 % for thermistors up to 18 GHz. A trial exercise for 3,5 mm sensors [10] shows uncertainties (k = 2) of 1,0 % – 2,0 % in the range between 18 GHz and 26 GHz. In the last two cases the measurements are performed using also other than microcalorimeter methods.

Already a decade ago a comparison [16] was carried out with emphasis on the reference output power of most power meters, viz. 1 mW at 50 MHz. Here the results show an uncertainty (k = 2) of 0,2 % – 0,7 % in the determination of the effective efficiency of the thermistor mounts.

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