New Broadband Thermal Noise Primary Standard in Coaxial Technology

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***Abstract* — A broadband primary standard for thermal noise measurements is presented and its thermal and electromagnetic behavior is analyzed by means of analytical and numerical simulation techniques. It consists of a broadband termination connected to a 3.5mm coaxial airline partially immersed in liquid Nitrogen. The main innovative part of the device is the thermal bead between inner and outer conductors, designed for obtaining a proper thermal contact and to keep low both its contribution to the total thermal noise and its reflectivity. A sensitivity analysis is realized in order to fix the manufacturing tolerances for a proper performance in the range 10MHz–26.5GHz.**

***Index Terms* — Thermal noise, metrology, broadband, coaxial line, metrology standard.**

I. INTRODUCTION

A primary noise standard is of key importance for microwave radiometry measurements, antenna temperature calibrations or evaluation of operation of low-noise amplifiers. Moreover, it allows the calibration of secondary standards, noise sources and noise measurement equipment, giving traceability to the measurement chain.

Different primary standards have been developed by national metrology institutes. Some examples are the French standards (LCIE) based on a set of waveguides ranging from 8.2 to 40GHz [1] or the German standards (PTB), both in waveguide (X-band, 12.4–18GHz) [2] and in coaxial technology (0.1–10GHz) [3]. These and other noise standards (NIST, NPL) are compared in [4]. The aim of this work is the development of a thermal noise primary standard with two main characteristics: very small uncertainties for noise temperature and broadband performance (at least 10MHz – 26.5GHz). The coaxial technology has been chosen in order to get this broadband behavior.

The reference for the standard design has been the NIST coaxial thermal noise primary standard described in [5], based on 7mm coaxial airline + termination in liquid Nitrogen, and working in the range 1–12.4GHz. The necessity of increasing the bandwidth to the range 10MHz – 26.5GHz requires the use of 3.5mm coaxial airline and a new design of different parts of the standard, in order to keep small values of noise temperature and reflectivity at the input port and, what is more important, accurate and stable values for these magnitudes.

In the next sections the new primary standard is presented and the influence of its different elements/characteristics (airline, termination, thermal bead, liquid Nitrogen level, etc.) on the reflection coefficient and on the noise temperature is analyzed in a rigorous way in order to establish the sensitivity to the different error sources and with the aim of prescribing manufacturing and operation tolerances for reducing the uncertainty.

II. NEW THERMAL NOISE PRIMARY STANDARD

The standard consists of a coaxial termination sunk in liquid Nitrogen connected to a 3.5mm airline which allows the temperature gradient from the 76K of liquid Nitrogen to the room temperature (297K). A water circuit in the port of the standard is necessary in order to force the room temperature in the upper edge of the line. Moreover, both the termination and the airline outer conductor are drilled in order to allow the liquid Nitrogen to go inside the termination and part of the airline, and allow the gas Nitrogen to go outside the airline in the upper part.

A 15cm. Maury 8043S (gold-plated Copper-Beryllium) was chosen as airline. After analyzing different broadband terminations, the Agilent 909D was chosen. It showed an increase of reflectivity when it was sunk in liquid Nitrogen, as Fig. 1 shows. The load was submitted to repeated cooling-heating cycles and it showed a good repeatability with very close values of reflectivity.

An equal temperature in the airline inner and outer conductor is assumed in the physical model for the calculation of the standard noise temperature. Therefore, a bead for providing thermal transfer between both conductors is necessary. Since the liquid Nitrogen is in contact with both conductors in the lower zone of the line, the bead is only necessary in the upper zone, at the position of the water circuit. The material for this bead must have a high thermal conductivity, but also a low electrical permittivity, since it is of key importance to make the bead as electromagnetically transparent as possible. Thus, a low dielectric constant will reduce the bead reflectivity and a low loss factor will reduce its losses. The beads for primary standard in [5] were made of Beryllium Oxide. Due to the high toxicity of this compound, an alternative material was searched. Different ceramics as Silicon Carbide, Aluminum Nitride, Boron Nitride or Shapal were founded as possible candidates. Finally, the Boron Nitride was chosen for substituting the Beryllium Oxide.

Table I shows the thermal conductivity and dielectric characteristics for both materials.

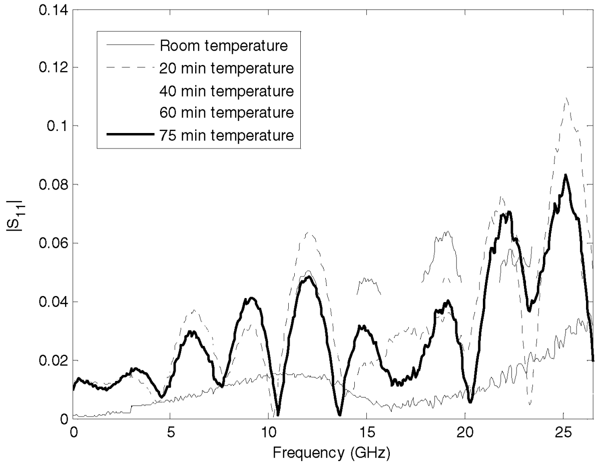

Fig. 1. Magnitude of the reflection coefficient in the Agilent 909D termination for room temperature and after immersion in liquid Nitrogen.

TABLE I

DIELECTRIC AND THERMAL PROPERTIES OF BEAD MATERIALS

Material	ε'	ε''	k_T (Wcm^{-1}K^{-1})
Beryllium Oxide [5]	6.5	$3.2\cdot10^{-4}$	2
Boron Nitride	4.0	$1.2\cdot10^{-3}$	0.7

Once the material has been chosen, the bead must be designed in order to minimize its electromagnetic impact in the standard, that is, to reduce as much as possible its reflection coefficient for the whole frequency range. In order to obtain thermal contact between the inner and outer conductor it is evident that the center of the bead must be in contact with both conductors. In this case, in order to obtain a characteristic impedance of 50Ω, the diameter of the inner conductor must be reduced as (1) points out. The bead is completed by two transitions adjacent to the bead center which are partially filled of dielectric in order to keep the 50Ω continuity. The effective permittivity of an inhomogeneous coaxial as that depicted in Fig. 2 is

$$\varepsilon_{ref} = \frac{\varepsilon_{r1}\varepsilon_{r2}\ln\frac{a}{b}}{\varepsilon_{r1}\ln\frac{c}{b}+\varepsilon_{r2}\ln\frac{a}{c}}\,. \tag{1}$$

Since material 1 is air/gas Nitrogen (ε_{r1}=1), the relation between radius a, b and c in order to obtain a 50Ω characteristic impedance must be

$$c = b\cdot\exp\left(\frac{\varepsilon_{r2}\left(36\ln^2\frac{a}{b}-25\right)}{36\ln\frac{a}{b}\left(\varepsilon_{r2}-1\right)}\right). \tag{2}$$

Fig. 3a shows a side section of the bead where a is constant, b changes linearly from its value in the airline to its value in the bead center, and c is given by (2). In order to reduce the difficulty of manufacturing, a stepped version of the bead (Fig. 3b) can be used. In this case, although the Z_0 continuity is preserved, the geometrical discontinuities increase the reflectivity. Fig. 4 shows the scattering parameter S_{11} magnitude for a stepped bead with a central zone of 5mm and three 3mm-steps at each side.

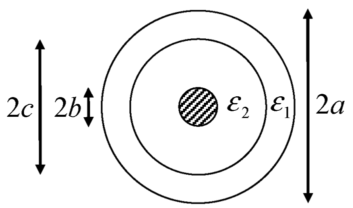

Fig. 2. Coaxial line section filled with two dielectric materials.

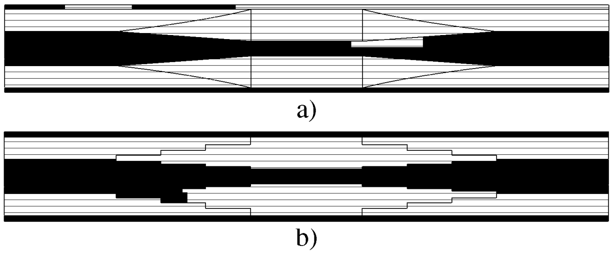

Fig. 3. Examples of thermal bead and inner conductor modification (patent pending): continuous (a) and stepped (b) transitions.

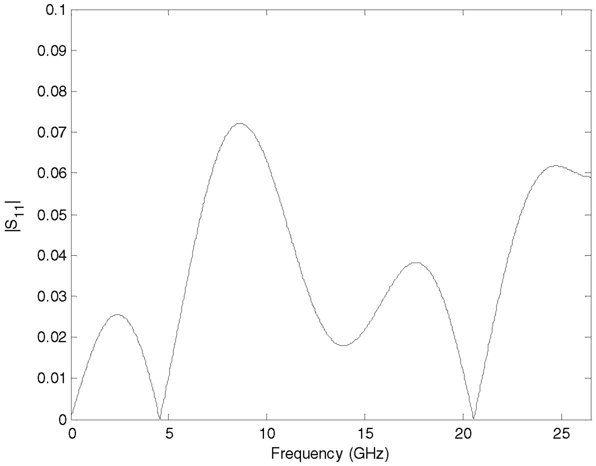

Fig. 4. Magnitude of S_{11} for a stepped design of the thermal bead.

III. NOISE TEMPERATURE CALCULATION

The noise temperature of the standard is the sum of the termination temperature (T_m) and the temperature added by the presence of the airline (ΔT). Moreover, this temperature must be corrected by the quantum factor χ:

$$T_s = \chi(T_m + \Delta T)\cdot \qquad (3)$$

The airline generates a noise temperature due to its temperature and losses and, on the other hand, attenuates the termination noise temperature. Therefore, the increment of the noise temperature due to the airline can be obtained as

$$\Delta T = \frac{2}{L}\int_0^l T(x)\alpha(x)L(x)dx + \frac{1-L}{L}T_m, \qquad (4)$$

where l is the line length, L is the total loss of the line, $T(x)$ is the temperature at point x, $\alpha(x)$ is the attenuation constant at point x and $L(x)$ is the accumulated attenuation at point x.

The calculation of $T(x)$ is made by a finite element simulation of the parabolic heat equation in Matlab™, obtaining the temperatures in the inner and outer conductor showed in Fig. 5.

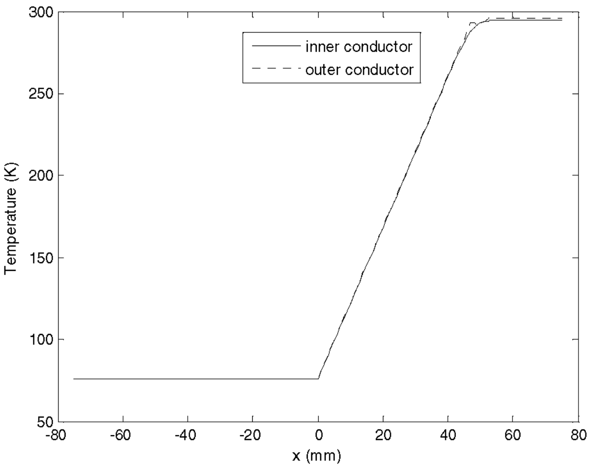

Fig. 5. Temperature distribution in inner and outer conductors.

The attenuation constant in x is the sum of the attenuation constant due to the conductor losses, α_c, and the attenuation constant due to dielectric losses α_d. This last contribution is taken into account only in the liquid Nitrogen ($\tan\delta = 5.2\cdot 10^{-5}$) and in the thermal bead stretches. For the thermal bead

$$\alpha_d = \frac{\pi}{\lambda_0}\sqrt{\varepsilon_{rBN}}\tan\delta_{BN}\frac{\ln\frac{c}{b}\left(\ln\frac{a}{b}\right)^{\frac{1}{2}}}{\left(\ln\frac{c}{b} + \varepsilon_{rBN}\ln\frac{a}{c}\right)^{\frac{3}{2}}}, \qquad (5)$$

where λ_0 is the vacuum wavelength and ε_{rBN} **and** $\tan\delta_{BN}$ are the Boron Nitride dielectric constant and loss tangent, respectively.

Assuming an homogeneous material for both conductors,

$$\alpha_c = \frac{R_S\sqrt{\varepsilon_r}}{240\cdot\pi a}\frac{1+\frac{a}{b}}{\ln\frac{a}{b}}, \qquad (6)$$

where R_S is the conductor surface resistance, which depends on the frequency and , through the resistivity, on the temperature. In the case of gold, the dependence of the resistivity with the temperature can be found in [6].

IV. REFLECTION COEFFICIENT CALCULATION

Although the reflection coefficient is not the reference magnitude of the standard, it is important to keep it low. Fig. 6 shows the different cascaded two-port networks in which the standard is divided in order to calculate its reflection coefficient. The reflection coefficient of the termination is measured; the scattering matrices of the liquid/gas Nitrogen discontinuity, those of the perforated stretch and the bead stretch of the airline are obtained by numerical simulations (Finite Difference Time Domain), and the reminder of scattering matrices in Fig. 6 are obtained by analytical expressions from transmission line theory. Results for the primary standard are shown in Fig. 7.

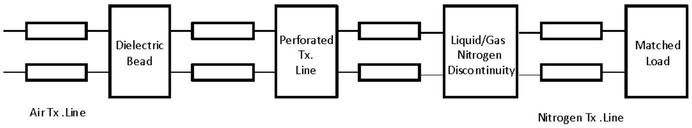

Fig. 6. Concatenation of the different parts of the primary standard.

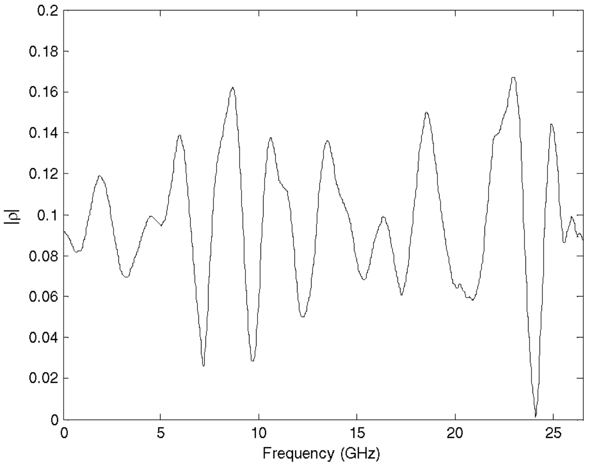

Fig. 7. Reflection coefficient of the primary noise standard.

IV. SENSITIVITY ANALYSIS

The following error contributions, following the analysis in [5], will be taken into account: uncertainty associated to ambient temperature T_a, uncertainty associated to the termination temperature T_m, changes in the resistivity of the conductors, changes due to the roughness of the walls, uncertainty associated to the temperature distribution along the air line and uncertainty associated to the loss tangent of the thermal bead.

The error due to T_m can have its origin in some of the following causes: uncertainty (± 0.01K) due to the pressure exerted by vapours generated by the Nitrogen, uncertainty (± 1 mm Hg) in the determination of atmospheric pressure, changes (± 3 cm) in the level of liquid Nitrogen considered as nominal, uncertainty due to a temperature gradient in the termination (0.1K) along its surface. The noise temperature error at the input of the noise standard, which is caused by these four contributions, is depicted as regards to the nominal case (case 0) in Figure 8 as case 1 and case 2. Figure 8 has been divided and reduced in frequency for sake of clarity. The uncertainty (± 1K) due to changes in water temperature T_a within the stabilization circuit is shown as case 3 and case 4.

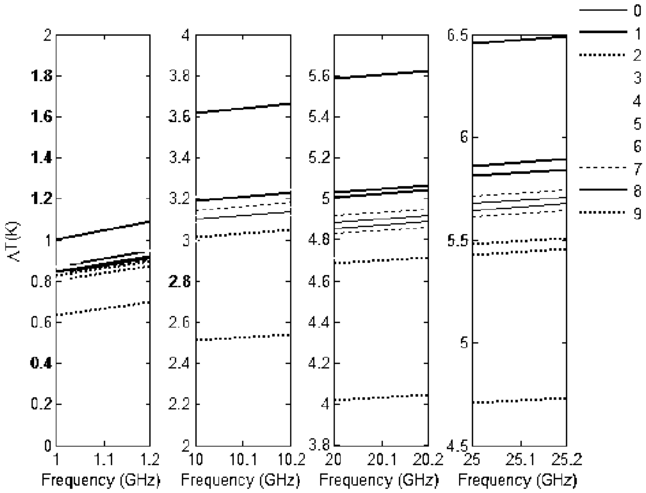

Fig. 8. Increase in noise temperature due to the airline.

An uncertainty in resistivity of ±5% is assumed. In this case, the error is due to an insufficient thickness in gold plating, as well as to other possible changes in resistivity. This uncertainty has its origin in the attenuation coefficient due to the air line conductor, which is assumed to be entirely produced by a gold conductor. This error is indicated as case 5 and case 6. Due to the fact that the surface of conductors is not perfectly smooth, there exists an area bigger than that estimated, which is absorbing the energy travelling along the air line. The effect of surface roughness is not very noticeable for the microwave frequency range, thus we assume that it introduces a change in attenuation less than 2%. This variation has been analysed as case 7. In order to compute the attenuation caused by the thermal bead, it is assumed that the uncertainty in tangent loss of material is less than 10%. The results obtained from the analysis of this variation are indicated as case 8 and case 9. As Fig. 8 shows, the cases with greater variation are case 1 and case 2. This is due to the fact that a variation in the level of liquid Nitrogen has been included: a change of ± 3cm in this level causes a noticeable deviation in the physical temperature of the structure with respect to its nominal value. The second greatest influence is due to the conductor resistivity (cases 5 and 6). Finally, we obtain the same order of magnitude for variations due to the tangent loss affecting dielectrics, T_a, and those caused by conductor roughness.

The uncertainty caused by internal reflections due (i) the non-perfect match between airline and termination, and (ii) the presence of the thermal bead have not been taken into account, but more work is envisaged in this direction.

V. CONCLUSIONS

A new primary noise standard that increases the frequency range of previous primary standards in coaxial technology, due to the use of a new thermal bead, has been described. The sensitivity analysis points out the liquid Nitrogen level as the main contribution to the noise temperature uncertainty. Therefore, level control mechanisms must be developed to reduce this error. Other results of this analysis allow to fix tolerances, as gold plating thickness or bead realization, in the standard manufacturing. Once the standard is realized, an international comparison with other primary standards must be realized in order to establish its performance.

REFERENCES

[1] J. Achkar, "A set of waveguide primary thermal noise standards and related calibration systems for the frequency range 8.2-40 GHz", *IEEE Transactions on Instrumentation and Measurement*, vol. 48, no. 2, pp. 638-641, April 1999.

[2] F.I. Buchholz, W. Kessel, "A New Primary Thermal Noise Standard at PTB for the Frequency Range 12.4 – 18.0 GHz", *IEEE Transactions on Instrumentation and Measurement*, vol. 42, no. 2, pp. 465-469, April 1993.

[3] F.I. Buchholz, W. Kessel, J. Niemeyer, "Improvements in the Accuracy of a New Coaxial Thermal Noise Standard", *IEEE Transactions on Instrumentation and Measurement*, vol. 38, no. 2, pp. 465-469, April 1989.

[4] J. Randa, J. Achkar, F.I. Buchholz, T. Colard, J. Rice, D. Schubert, M. Sinclair, G.K. Williams, "International Comparison of Thermal Noise-Temperature Measurements at 2, 4, and 12 GHz", *IEEE Transactions on Instrumentation and Measurement*, vol. 48, no.2, pp. 174-177, April 1999.

[5] NBS Technical Note 1074: *A Coaxial Noise Standard for the 1GHz to 12.4 GHz Frequency Range*. NIST, 1984.

[6] D. R. Lide, *Handbook of Chemistry and Physics. 75th Edition*, New York: CRC Press, 1996-1997.