Simple and Accurate Method for Microwave Noise Parameters Calculation

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Abstract. *This paper proposes a new method for microwave two-port noise parameters values extraction. The method is based on a set of simple and accurate formulas which allows the noise characterization without any optimization procedure. The measurements were performed using a system based on a short cascaded with a long transmission line and a passive two-port designed to exhibit versus frequency a behavior close to a transistor. The results presented for a measurement example show good agreement with those obtained using an optimization procedure.*

The new extraction method based on the frequency variation noise measurement principle and used with a simple hardware can be a practical tool for workers in the field.

Keywords

Noise measurement, noise parameters, noise wave model.

1. Introduction

Recently, a broadband noise measurement system that completely characterizes the noise temperature of linear two-port system according to both standard methods was presented [1]. The system is based on a long transmission line and frequency variation principle. It allows measurements through the classical y-factor method or the "cold source" method. The results produced by both methods are good and similar.

The principal drawback of the y-factor method is that it requires a mismatched noise source which should be carefully built and calibrated [2]. However, with the cold source method or the z-factor method as it is called in reference [1], this kind of noise source is not required and only a short cascaded with a long transmission line is used to accomplish the mismatched measurements.

The present paper develops an alternative method for the noise parameters calculation. The method is based on a set of simple and accurate formulas derived from the wave model of the noise temperature function of a linear two-port.

The following section contains a review of the wave formalism used in this work to describe the two-port noise parameters. Section 3 presents the experimental setup and the noise measurement method. In section 4, the new method is described and formulas for noise parameters calculations are derived. The experimental results and their comments are given in section 5. Conclusions are given in the last section.

2. The Noise Wave Model and the T_a, T_b, T_c, and φ_c Noise Parameters

The classical form of the relationship between the noise temperature of a linear two-port at a given frequency and the source reflection factor is given by [3]:

$$T_n(S) = T_m + T_d \frac{|S - S_o|^2}{1 - s^2} \quad (1)$$

where $S = s\exp(j\varphi)$ is the complex source reflection factor, $S_o = s_o\exp(j\varphi_o)$ is the optimum source reflection factor, T_m is the minimum noise temperature and T_d is the coefficient indicating how fast T_n increases when S gets different from S_o.

The noise parameters extraction method presented in this paper is based on the noise wave model of a linear two-port proposed by R.P. Meys [3] and shown in Fig. 1. With this model, the noise is represented by two correlated noise wave sources A_n and B_n whereas the signal properties are described by the wave transfer matrix noted here W. An interesting feature of the model is the very compact expression of the noise temperature it leads to [3]:

$$T_n(S) = T_n(s,\varphi) = \frac{T_a + s^2 T_b + 2sT_c\cos(\varphi + \varphi_c)}{1 - s^2} \quad (2)$$

where T_a is the temperature defining the level of A_n, T_b is the temperature defining the level of B_n and $T_c\exp(j\varphi_c)$ is the correlation temperature between both sources. Conversion formulas between the parameters in (1) and (2) are given in [3].

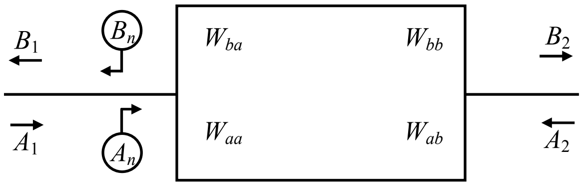

Fig. 1. The noisy two-port model using two correlated input noise wave sources associated with the wave transfer matrix W.

From (2) we can deduce that, if the reflection factor turns on a circle like in Fig. 2, the evolution of the noise temperature $T_n(\varphi)$ will be as shown in Fig. 3.

Hence, parameters T_b and T_c can be obtained from the mean noise temperature $\overline{T_n}$ and the amplitude of the noise temperature ΔT_n, respectively. The argument φ_c is derived from the source reflection factor phase φ_o that minimizes $T_n(\varphi)$.

In other hand, parameter T_a is obtained experimentally with a matched source (*i.e.* $s = 0$).

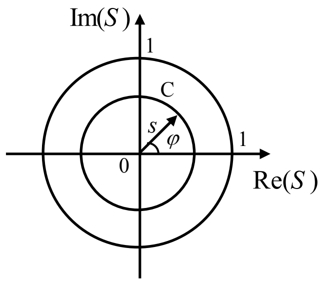

Fig. 2. A constant s circle in the reflection factor plane.

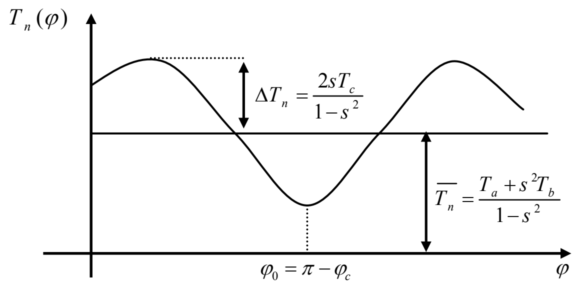

Fig. 3. Noise temperature evolution along circle C.

Let us suppose m mismatched noise temperature measurements T_{nmi} made along circle C, that means with constant s and phases φ_{mi} regularly spread over 360 deg:

$$\varphi_{mi} = \varphi_{m0} - i\,2\pi / m \tag{3}$$

with $i = 0, 1,\ldots, (m\text{-}1)$ and φ_{m0} is the arbitrary initial phase.

From trigonometric proprieties, we can show that:

$$\sum_0^{m-1} \cos(\phi_{mi} + \phi_c) = 0\,. \tag{4}$$

Considering the equation (4), it is shown in [4] that the values of T_b, T_c and φ_c that minimize the squares of the errors between the model and the measurements are obtained through the following formulas:

$$T_b = \frac{\frac{1}{m}(1-s^2)\cdot\sum_0^{m-1} T_{nmi} - T_a}{s^2}\,, \tag{5}$$

$$T_c = \frac{(1-s^2)}{2s} P_2\,, \tag{6}$$

$$\varphi_c = P_1\,, \tag{7}$$

with

$$P_1 = \tan^{-1}\left[-\frac{\sum_0^{m-1} T_{nmi}\sin(\varphi_{mi})}{\sum_0^{m-1} T_{nmi}\cos(\varphi_{mi})} \right], \tag{8}$$

$$P_2 = \frac{2}{m}\sum_0^{m-1} T_{nmi}\sin(\varphi_{mi} + P_1)\,. \tag{9}$$

It is noted that the value of P_1 given by (8) is undefined by π. We choose its value for P_2 and T_c to be positive.

3. Experimental Setup and Measurement Method

An overview of the measurements set-up is given in Fig. 4. The measurement method is based on the frequency variation principle [5-7]. With this method, the non-zero source reflection factor S_i needed for defining the noise temperature function is created by a short (SHO) plus a Long Transmission Line (LTL). However, changing the phase φ of this reflection factor (on a circle like C in Fig. 2) is done by slightly shifting the frequency around the central frequency measurement.

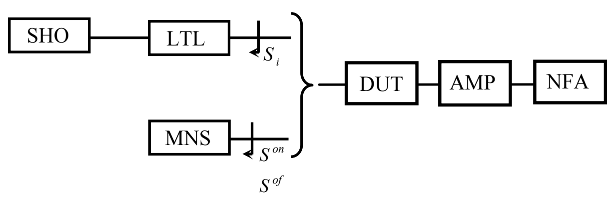

Fig. 4. General overview of the set-up.

The MNS is a two sates noise source characterized by S^{off}, T_{off} (with solid state sources $T_{off} = T_p$ the physical or ambient temperature) and S^{on}, T_{on}.

The transmission line used is a Tektronix type 113 delay line. It contains about 15m low-loss semi-rigid cable.

The Device Under Test (DUT) can be any linear two-port. For testing the set-up, we used a special passive two-port that will be described later.

The amplifier AMP is either a Miteq JS2-01002000-09-10A 100 MHz to 2 GHZ low noise amplifier or a Mini-Circuits ZX60-33LN-S 50 MHz to 3 GHz amplifier. The NFA is an Agilent N8973A Noise Figure Analyzer.

The available noise power at the output of the receiving chain equals to the equivalent available noise power at the input times the available power gain of the DUT/receiver.

The available output noise power is measured in the following circumstances:

a) With the source off ($T_s = T_p$), leading to:

$$PW_0^{off} = G_{adr}(S^{off}) \cdot k \cdot BW_n \cdot (T_n(S^{off}) + T_p) \quad (10)$$

b) With the source on ($T_s = T_{on}$), leading to:

$$PW_0^{on} = G_{adr}(S^{on}) \cdot k \cdot BW_n \cdot (T_n(S^{on}) + T_{on}) \quad (11)$$

c) With a series of mismatched reflection factors S_i, chosen along circle C in Fig. 2 ($T_s = T_p$), leading to:

$$PW_{mi} = G_{adr}(S_i) \cdot k \cdot BW_n \cdot (T_n(S_i) + T_p) \quad (12)$$

where $G_{adr}(S_i/S^{on/off})$ and $T_n(S_i/S^{on/off})$ designate the available power gain and the noise temperature of the DUT/receiver, respectively. BW_n is the measurement bandwidth, k the Boltzmann's constant and T_s is the source temperature.

Dividing (11) by (10) we get the y-factor:

$$y = \frac{PW_0^{on}}{PW_0^{off}} = \frac{G_{adr}(S^{on})}{G_{adr}(S^{off})} \frac{T_n(S^{on}) + T_{on}}{T_n(S^{off}) + T_p}. \quad (13)$$

Neglecting the change of the source reflection factor between the on and off source states (phenomenon called the "on/off" effect), and assuming that $S^{on} = S^{off} = 0$, then equation (13) becomes:

$$y_0 = \frac{T_a + T_{on}}{T_a + T_p} \quad (14)$$

from which a first order approximation for T_a is derived as follows:

$$T_{a0} = \frac{T_{on} - y_0 T_p}{y_0 - 1} \quad (15)$$

By other way, dividing (12) by (10), we get the z-factor:

$$z_i = \frac{PW_{mi}}{PW_0^{off}} = \frac{G_{adr}(S_i)}{G_{adr}(S^{off})} \frac{T_n(S_i) + T_p}{T_n(S^{off}) + T_p}. \quad (16)$$

Considering that the available power gain is given by [8]:

$$G_a(S) = |S_{21}|^2 \frac{1 - |S|^2}{|1 - S_{11}S|^2 - |S_{22} - \Delta_S S|^2} \quad (17)$$

with $\Delta_S = S_{11} S_{22} - S_{12} S_{21}$ and $S_{12} = 0$ for the DUT/receiver chain. Thus, expression (16) can be rewritten as follows:

$$z_i = \frac{1 - s_i^2}{1 - (s^{off})^2} \frac{|1 - S_{dr} S^{off}|^2}{|1 - S_{dr} S_i|^2} \frac{T_n(S_i) + T_p}{T_n(S^{off}) + T_p} \quad (18)$$

where S_{dr} is the DUT/receiver input reflection factor.

Then, the expression of the noise temperature is given by:

$$T_n(S_i) = z_i \frac{1 - (s^{off})^2}{1 - s_i^2} \frac{|1 - S_{dr} S_i|^2}{|1 - S_{dr} S^{off}|^2} (T_n(S^{off}) + T_p) - T_p. \quad (19)$$

Assuming that $T_n(S^{off}) = T_a$, we get:

$$T_n(S_i) = z_i \frac{1 - (s^{off})^2}{1 - s_i^2} \frac{|1 - S_{dr} S_i|^2}{|1 - S_{dr} S^{off}|^2} (T_a + T_p) - T_p. \quad (20)$$

From the $T_n(S_i)$ measurements, the parameters T_b, T_c, and φ_c are derived using the formulas which will be presented in the next section.

4. Noise Parameters Calculation Method

The expressions (5) to (7) and expression (15) give a first order approximation of the noise parameters. However, because of some experimental errors, these expressions are not sufficiently accurate due to:

a) The reflection factor of the matched noise source is not perfectly zero;

b) The matched noise sources exhibit some on/off effect;

c) The modulus of the reflection factor of the short plus long line combination somewhat changes when the frequency is swept over the Δf band in order to achieve the different phases. (Fig. 5.b),

d) With the frequency variation procedure the phases φ_{mi} could not be exactly regularly spread over 360 deg. This makes the term in (4) to be different from zero.

To address theses problems and obtain more accurate formulas for noise parameters determination, we will adopt the following procedure:

A. Firstly:

By considering the changes of the modulus of the reflection factor of the short plus long line combination (s is not constant). The formulas (5) to (7) are rewritten as follows:

$$T_{b0} = \frac{\sum_0^{m-1} T_{nmi}(1 - s_i^2) - m T_{a0}}{\sum_0^{m-1} s_i^2}, \quad (21)$$

$$\varphi_{c0} = \tan^{-1}\left[-\frac{\sum_0^{m-1} T_{nmi}(1 - s_i^2) s_i \sin(\varphi_{mi})}{\sum_0^{m-1} T_{nmi}(1 - s_i^2) s_i \cos(\varphi_{mi})} \right], \quad (22)$$

$$T_{c0} = \frac{\sum_{0}^{m-1} T_{nmi}\,(1-s_i^2)s_i\,\cos(\varphi_{mi}+\varphi_{c0})}{\sum_{0}^{m-1} s_i^2}. \qquad (23)$$

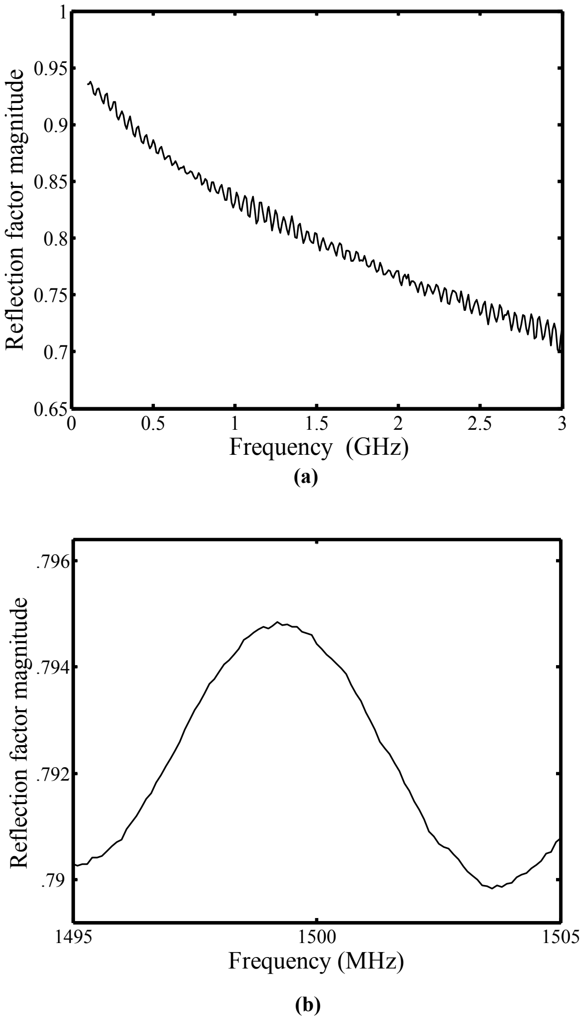

Fig. 5. The reflection factor of the short plus long transmission line assembly (modulus). (a) Over the 100 MHz to 2.9 GHz Band. (b) Around the 1.5 GHz frequency.

B. Secondly:

The noise parameters values obtained using the formulas (21) to (23) and (15) are used to calculate a more accurate approximation of theses parameters by mean of the expressions developed in the following paragraphs.

The parameter T_a is calculated from the matched measurement. Replacing $G_{adr}(S^{on})$, $G_{adr}(S^{off})$, $T_n(S^{on})$ and $T_n(S^{off})$ in expression (13) and after some manipulations, we obtain:

$$T_a = \frac{S_{inj}(s^{on})^2 - y\,(s^{off})^2}{y - S_{inj}}T_{b0} + \frac{S_{inj}T'_{on} - yT'_{p}}{y - S_{inj}} + 2\frac{S_{inj}s^{on}\cos(\varphi_{c0}+\varphi_s^{on}) - y\,s^{off}\cos(\varphi_c+\varphi_s^{off})}{y - S_{inj}}T_{c0} \qquad (24)$$

with $T'_{on} = T_{on}(1-(s^{on})^2)$, $T'_{p} = T_{p}(1-(s^{off})^2)$ and $S_{inj} = \dfrac{\left|1 - S_{dr}S^{off}\right|^2}{\left|1 - S_{dr}S^{on}\right|^2}$.

The parameter T_b can be obtained without any approximation from the mean values of the noise temperature measurements. Using (2), we can write the sum of the m noise temperature measurements T_{nmi} as follows:

$$\frac{1}{m}\sum_{0}^{m-1} T_{nmi}(1-s_i^2) = T_a + \frac{1}{m}T_b\sum_{0}^{m-1}s_i^2 + \frac{2}{m}T_c\sum_{0}^{m-1}s_i\cos(\varphi_{mi}+\varphi_c). \qquad (25)$$

Then, the parameter T_b is derived as follows:

$$T_b = \frac{\sum_{0}^{m-1} T_{nmi}(1-s_i^2) - mT_a - 2T_{c0}\sum_{0}^{m-1}s_i^2\cos(\varphi_{mi}+\varphi_{c0})}{\sum_{0}^{m-1}s_i^2}. \qquad (26)$$

According to the "Least Square Method" [9, 10], the parameters T_c and φ_c are chosen in order to obtain the best agreement between the measurement and the model. Hence, we define an error function which gives the difference between the measurements and the ideal curve (2) as follows:

$$ErrF = \sum_{0}^{m-1}\left((1-s_i^2)T_{nmi} - T'_{nci}\right)^2 \qquad (27)$$

where $T'_{nci} = (1 - s_i^2)T_{nci} = T_a + s_i^2T_b + 2T_c\, s_i\cos(\varphi_{mi}+\varphi_c)$. The parameter T_{nci} represents the computed noise temperature for the mismatched noise source reflection factor.

The calculus of the derivation of the function $ErrF$ according to T_c and φ_c gives:

$$T_c = \frac{\sum_{0}^{m-1}((1-s_i^2)T_{nmi} - T_a - s_i^2T_{b0})s_i\cos(\varphi_{mi}+\varphi_{c0})}{\sum_{0}^{m-1}s_i^2 + \sum_{0}^{m-1}s_i^2\cos 2(\varphi_{mi}+\varphi_{c0})}, \qquad (28)$$

$$\varphi_c = \tan^{-1}\left[-\frac{\sum_{0}^{m-1}((1-s_i^2)T_{nmi} - T_m - s_iT_{c0})s_i\sin(\varphi_{mi})}{\sum_{0}^{m-1}((1-s_i^2)T_{nmi} - T_m - s_iT_{c0})s_i\cos(\varphi_{mi})}\right] \qquad (29)$$

with $T_m = T_a + s_i^2T_{b0}$.

Since the analytical solution of the equation $(\partial ErrF/\partial\varphi_c) = 0$ is very complicated, the following good approximation was assumed in deriving the expression of the parameter φ_c:

$$\sum_{0}^{m-1}s_i^2\cos 2(\varphi_{mi}+\varphi_{c0}) = \sum_{0}^{m-1}s_i^2\cos(\varphi_{mi}+\varphi_{c0}). \qquad (30)$$

5. Experimental Results and Noise Parameters Determination

To test the accuracy of the proposed formulas, we use as a DUT a special linear passive two-port. This verification procedure was used by many authors in the field [11], [12]. For a passive device, the noise parameters can be derived from its signal parameters [13]:

$$T_a = T_p \cdot (|W_{ab}|^2 - |W_{aa}|^2 - 1), \tag{31}$$

$$T_b = T_p \cdot (|W_{bb}|^2 - |W_{ba}|^2 + 1), \tag{32}$$

$$T_c \cdot e^{j\varphi_c} = T_p \cdot (W_{ba}^* W_{aa} - W_{bb}^* W_{ab}). \tag{33}$$

These noise parameters only rely on four complex signal parameters. For this reason, they are believed to be much more accurate. Also, the discrepancies between them and the parameters derived from the noise measurements are a good approximation of the errors made by the system.

As it is shown in [1], the DUT built by a transmission line section followed by an attenuator (Fig. 6) exhibits both small and large optimum reflection factor versus frequency. By this way, we have a device that exhibits a behavior versus frequency close to a transistor but with loss rather than gain. This makes the device even more difficult to measure, as the second stage contribution becomes significant, providing a severe test for the system.

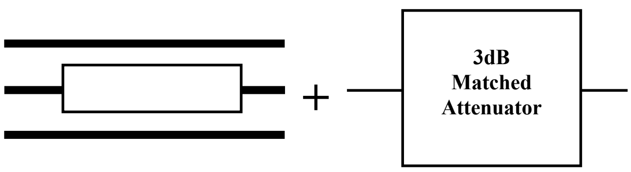

Fig. 6. The special DUT for testing the set-up. The mismatched line section has a 25 Ω characteristic impedance and is quarter wave at 1.5 GHz.

Measurements are down over the 100 MHz to 2.9 GHz band. We measured the over all noise parameters with this assembly as DUT (T_{a12}, T_{b12}, T_{c12}, φ_{c12}). Then, we measured the receiver noise parameters (T_{a2}, T_{b2}, T_{c2}, φ_{c2}).

The second stage correction formulas given in [13] allow to compute the DUT noise parameters T_{a1}, T_{b1}, T_{c1}, and φ_{c1} as follows:

$$T_{a1} = T_{a12} - |W_{ab1}|^2 T_{a2} - |W_{aa1}|^2 T_{b2} + 2\,\mathrm{Re}(W_{ab1}^* W_{aa1} T_{c2} e^{j\varphi_{c2}}), \tag{34}$$

$$T_{b1} = T_{b12} - |W_{bb1}|^2 T_{a2} - |W_{ba1}|^2 T_{b2} + 2\,\mathrm{Re}(W_{bb1}^* W_{ba1} T_{c2} e^{j\varphi_{c2}}), \tag{35}$$

$$\begin{aligned} T_{c1} e^{j\varphi_{c1}} = T_{c12} e^{j\varphi_{c12}} &- W_{ab1}^* W_{ba1} T_{c2} e^{j\varphi_{c2}} - W_{aa1}^* W_{bb1} T_{c2} e^{-j\varphi_{c2}} \\ &+ W_{ab1}^* W_{bb1} T_{a2} \quad + W_{aa1}^* W_{ba1} T_{b2}. \end{aligned} \tag{36}$$

Although all the results for this paper will be given in terms of the parameters T_a, T_b, T_c, and φ_c, equivalent results for the conventional IEEE parameters (S_o, F_{min} and R_n) can be easily obtained using the relations given by [14].

Fig. 7 to Fig. 9 compare the noise parameters calculated using the new calculation method (cross) and those obtained by the method presented in [1] (circles) to those derived from the S-parameters measurements (solid lines).

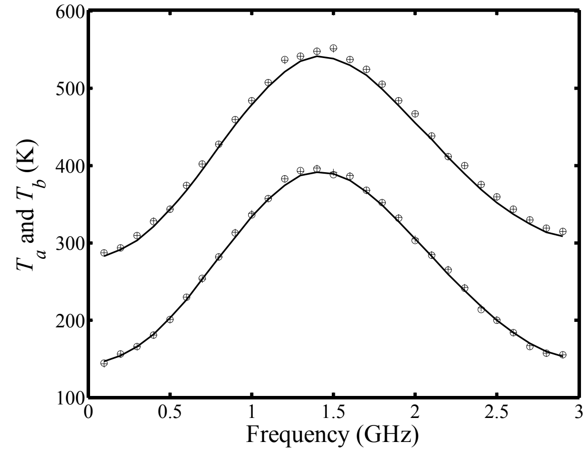

Fig. 7. Parameters T_a (upper curve) and T_b (lower curve) versus frequency.

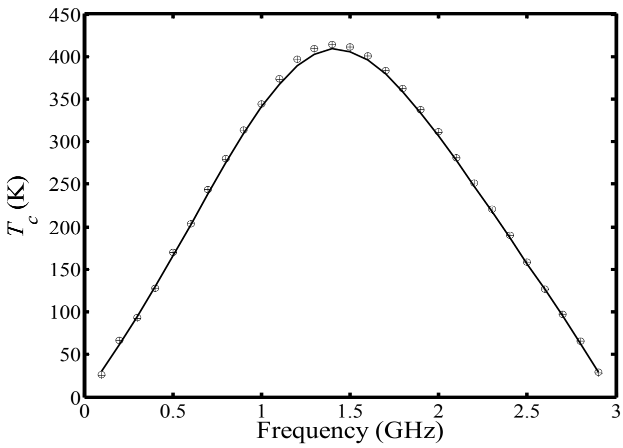

Fig. 8. Parameter T_c versus frequency.

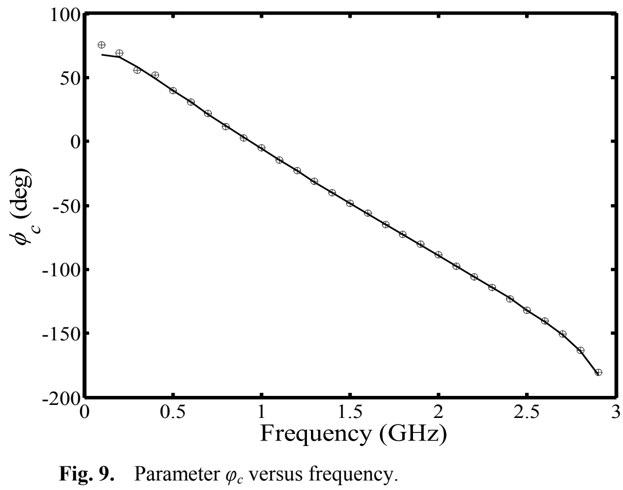

Fig. 9. Parameter φ_c versus frequency.

Fig. 10 to Fig. 13 show the discrepancies between the parameters obtained from the noise measurement and those obtained from the S-parameters measurements.

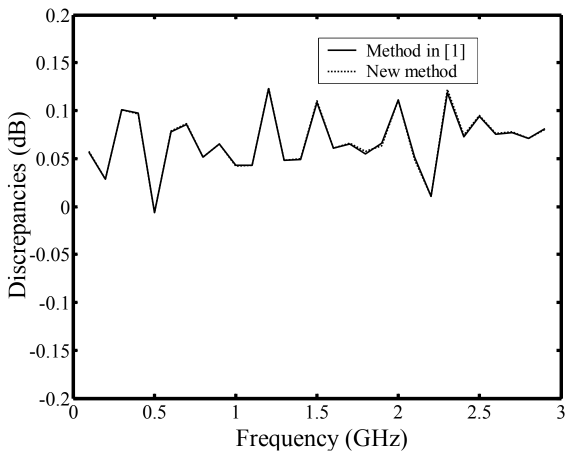

Fig. 10. Discrepancies versus frequency for parameter T_a.

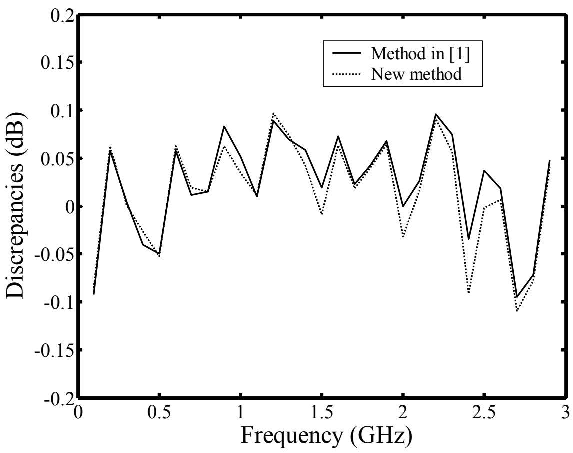

Fig. 11. Discrepancies versus frequency for parameter T_b.

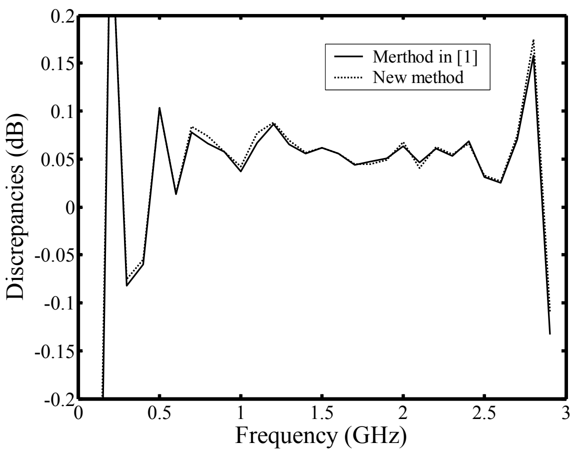

Fig. 12. Discrepancies versus frequency for parameter T_c.

As can be seen by examining these figures the proposed formulas give a good approximation for the noise parameters. Also, the results show good agreement with those obtained using an optimization procedure.

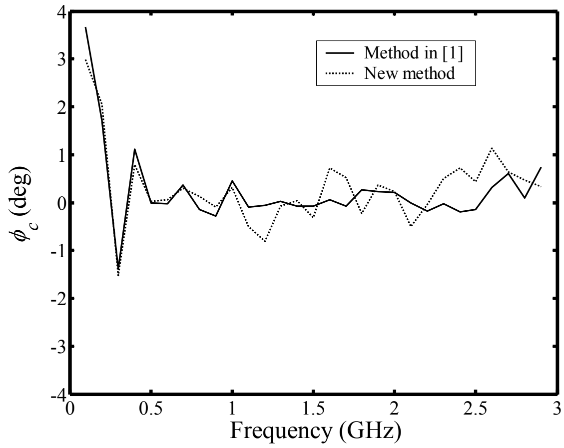

Fig. 13. Discrepancies versus frequency for parameter φ_c.

Tab. 1 shows the RMS discrepancies for each parameter and both methods. It confirms that the differences are very slight.

Parameter	New Method	Method in [1]
T_a (dB)	0.0750	0.0746
T_b (dB)	0.0565	0.0565
T_c (dB)	0.1444	0.1613
φ_c (deg)	1.7249	1.7142

Tab. 1. RMS discrepancies.

6. Conclusions

A new method for extracting noise parameters values of microwaves device is developed in this paper. The measurement was performed on a special passive two-port allowing comparison of the noise parameters values from S-parameters and noise measurement. As the measurement example has shown, the proposed method allows an accurate determination of the noise parameters, without the use of any complex optimization routine. This gives an alternative simple and practical extracting procedure for microwaves noise characterization. It is pointed out that the method can be easily adapted for any other measurement hardware which can create the required source reflection factor configuration.

In a future work, it is interesting to test the proposed method on an active network, and perform a statistical analysis of the uncertainties in the noise parameters measurements which allows a deep evaluation of the extraction method presented in this paper.

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