Development of a Verification Technique for On-wafer Noise Figure Measurement Systems

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***Abstract* —We present the development of a verification technique for on-wafer noise figure (NF) measurement systems. As the key element of the technique, a verification device consisting of a mismatched attenuator and a low noise amplifier (LNA) has been developed. The attenuator and the LNA are fabricated on two separate chips but joined with a bondwire. The verification procedure based on the device has also been developed and tested on an on-wafer vector network analyzer system with a noise measurement option across the frequency range from 2 GHz to 20 GHz. It has also been found that the bondwire contributes to negligible effect on the system when NF is high e.g. 3 dB but slightly higher when NF is smaller e.g. 1 dB.**

***Index Terms* —Noise figure measurement, Noise parameters, On-wafer measurement, Verification method.**

I. INTRODUCTION

Low noise Amplifiers (LNAs) are critical devices in many applications such as communication systems, medical instruments, and imaging systems. Noise figure (NF) is one of the most important parameters for assessing the quality of an LNA because it indicates any excess noise that the LNA produces. Accurate measurement on NFs ensures the design and fabrication of low noise circuits and systems are robust and accurate. Commercial NF measurement instruments such as NF analyzers have been available for many years. Recent advances in vector network analysers (VNA) technology provide even higher accuracy than the conventional NF noise analysers by using the so-called the source vector-error corrected cold-source NF measurement technique or source-corrected NF measurement technique [1]. The technique takes advantage of VNA's capability of characterizing mismatches at the test port and the internal source and can correct any mismatches related to measurement errors for NF measurements. This is especially useful for on-wafer and fixture type of NF measurement systems because they have greater mismatches compared with a coaxial system.

To verify a NF measurement system, one of the commonly used practices is to use a verification device or standard such as an attenuator, a short transmission line, an isolator, a "cold" FET or a Lange coupler [2-5]. By measuring the *S*-parameters of the verification device，NF can be derived and compared against those measured using a verified noise measurement system [6, 7]. The advantage of this type of verification devices is that they can solely generate thermal noise and the noise performance is predictable and repeatable if the ambient temperature is well-controlled [5]. On the contrary, the disadvantage is that the measured NFs are not related to the injected noise signal but strongly dependent on source match. Thus, it cannot be used to verify the full capability of a noise measurement system [8].

Van den Bosch and Martens proposed an active device verification procedure [9] in which a 'gold' reference amplifier whose NF is measured at one of metrology laboratories was proposed by V. Adamian [10]. The advantage of this method is that those active verification devices have very similar test conditions as those of the devices-under-test (DUTs). However, the disadvantage is that it's large uncertainty due to drift and change of ambient conditions. For example, a measurement error of up-to 40% was reported in [9].

Recently, another method of using a passive two-port network cascaded to an amplifier as a verification device was proposed [8,11,12] in which the noise parameters (NPs) of the passive device and the amplifier were measured separately and then summed. The total NP was compared with the measured NP when they were cascaded. The NP of the passive device was derived from its S-parameters and the ambient temperature. This method was demonstrated effective in a coaxially configured measurement system [8, 11]. However, the NF shown in those examples is more than 3 dB which is much higher than that of a LNA. The NF could be, for example, as low as 1dB for ultra wideband low noise amplifiers operating in the frequency range of 2 GHz-20 GHz [13]. In addition, based on authors' knowledge this technique has never been reported for verifying an on-wafer NF measurement system.

In this paper, we propose a novel verification technique for on-wafer NF measurement systems. A verification artifact that consists of two separate on-chip devices namely a mismatched attenuator and an auxiliary amplifier and joined by a bondwire is developed. Unlike reported in [9, 10] where the active device was used as a reference device, we use the passive device instead. By using this method, higher accuracy and reproducibility can be obtainable. In addition, this method also allows one to carry out NF measurements on amplifiers at their development stage. We show the theory of the verification technique based on the proposed passive as the reference device and demonstrate the performance of the verification device across the frequency range from 2 GHz to 20 GHz.

II. THEORY

Figure 1 show the noise wave models of a single linear two-port network and a cascaded two-port network [7]. For a single linear two-port network, we have

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix} + \begin{bmatrix} a_{n1} \\ b_{n1} \end{bmatrix} \quad (1)$$

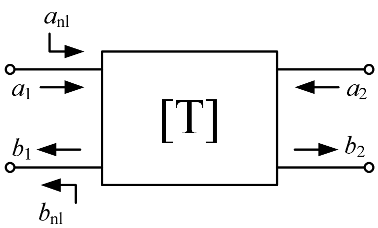
The S-parameter and the transmission parameter of the two-port network has the following relationship

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \frac{1}{t_{11}} \begin{bmatrix} t_{21} & t_{11}t_{22} - t_{21}t_{12} \\ 1 & -t_{12} \end{bmatrix} \quad (2)$$

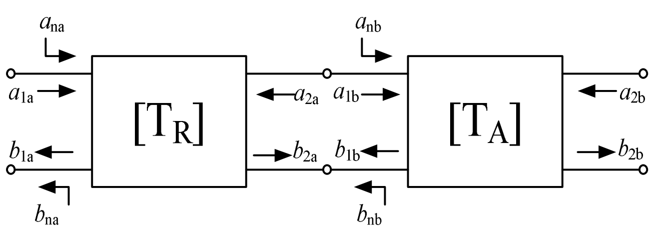
The noise correlation matrix of the two-port network is written as

$$\mathrm{C} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} = \begin{bmatrix} \overline{|a_{n1}|^2} & \overline{a_{n1}b_{n1}^*} \\ \overline{b_{n1}a_{n1}^*} & \overline{|b_{n1}|^2} \end{bmatrix} \quad (3)$$

where the asterisk represents the complex conjugate.



(a)



(b)

Fig. 1. Noise wave models for a single linear two-port network (a) and a cascaded two-port network (b).

For a cascaded two-port network, we have [7]

$$[T_C] = [T_R] \cdot [T_A] \quad (4)$$

$$[C_R] = [C_C] - [T_R] \cdot [C_A] \cdot [T_R]^H \quad (5)$$

where $[T_R]$ and $[T_A]$ are transmission matrices of the reference and the auxiliary device, respectively and $[C_R]$ and $[C_A]$ are the noise correlation matrices of the reference and auxiliary device respectively. $[T_R]^H$ is the conjugate transpose of $[T_R]$. $[T_C]$ and $[C_C]$ are transmission matrices and noise correlation matrices of the cascaded two-port network.

The noise correlation matrix can be measured directly using a noise measurement system therefore once $[C_C]$ and $[C_A]$ are available and the noise correlation matrix of the verification device $[C_R]$ can be derived. Since the noise correlation matrix of a passive device can also be derived from its S-parameters and the temperature as following [14]

$$\mathrm{C} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} = \frac{T_a}{T_0} \{[T] \cdot [P_t] \cdot [T]^H - [P_t]\} \quad (6)$$

where T_a is the ambient temperature, T_0=290K, T^H is the conjugate transpose transmission matrix of T and

$$P_t = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

T is related to the *S*-parameter as shown in (2), and therefore the noise correlation matrix can be also derived from its *S*-parameter which can be measured using a vector network analyzer (VNA).

We first compare the measured noise correlation matrix using the above two methods and then work out how the noise measurement system perform quantitatively. In fact, it is not common to use the noise correlation matrix to evaluate a test system but the NF F which has the following relationship with the noise correlation matrix,

$$F = F_{min} + \frac{4R_n}{Z_0} \frac{|\Gamma_s - \Gamma_{opt}|^2}{\left(1-|\Gamma_s|^2|1+\Gamma_{opt}|^2\right)} \quad (7)$$

$$F_{min} = \frac{c_{11}-c_{22}}{2} + \frac{\sqrt{(c_{11}+c_{22})^2 - 4|c_{12}|^2}}{2} + 1 \quad (8)$$

$$|\Gamma_{opt}| = \frac{c_{11}+c_{22}}{2|c_{12}|} - \sqrt{\left(\frac{c_{11}+c_{22}}{2|c_{12}|}\right)^2 - 1} \quad (8)$$

$$\angle\Gamma_{opt} = \tan^{-1}\left(\frac{imag(c_{12})}{real(c_{12})}\right) \quad (10)$$

$$R_n = \frac{Z_0|c_{12}|}{4|\Gamma_{opt}|}\left[1 + 2|\Gamma_{opt}|\csc(\angle\Gamma_{opt}) + |\Gamma_{opt}|^2\right] \quad (11)$$

where Z_0 is the characteristic impedance of the measurement system which is 50 Ohm in this case. Γ_S is the source reflection coefficient. Since we validate NF, it is equal to zero. Thus, we can verify a NF measurement system by comparing F of the passive device obtained using the two different methods. The verification procedure can be summarized as follow:

1. Measure the *S*-parameters of the passive device alone using a calibrated VNA system and work out the NF using (7-11) as the reference value (F_s)
2. Measure the noise correlation matrix of the LNA alone using the noise option of a VNA
3. Cascade the LNA to the passive device and then repeat the measurement as 2 to obtain the noise correlation matrix of the cascaded device
4. Calculate the noise correlation matrix of the passive by removing the NP of the LNA from that of the combined configuration and work out the NF （F_m） using (7-11)
5. Compare the measured noise figure (F_m) against the reference noise figure (F_s)

The aforementioned procedure can be easily implemented in a coaxial system but not for an on-wafer system. For the former, devices are connectorised and can be easily joined and disjoined; however, this is not the case for the latter. Fig. 2 illustrates the solution that we are proposing for cascading two on-wafer devices so that similar verification procedure used in the coaxial system can be used for the on-wafer system. Note microstrip technology was implemented to maximize its bandwidth.

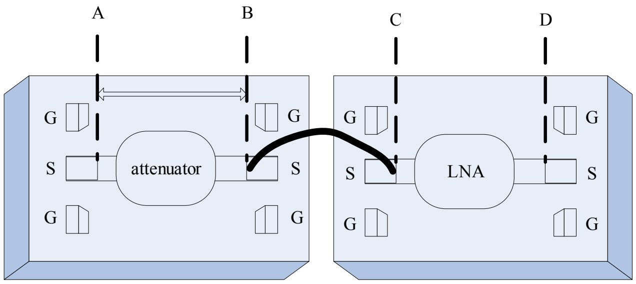


Fig. 2. Illustration of the proposed cascaded on-wafer verification device. Reference planes for each individual device are also shown.

On the left is a mismatched attenuator which is used as the reference device because of its steady noise performance. On the right is an LNA which is used as an auxiliary device. The attenuator and the LNA are connected using a bondwire. In fact, the verification procedure for an on-wafer NF measurement system is slightly different from that for a coaxial system because of the addition of the bondwire. The procedure for on-wafer system verification is illustrated in Fig. 3. The main difference between the two verification procedures is the involvement of removing the contribution of the bondwire. The bondwire that is used to link the passive with the LNA may have the effect on the overall performance of the verified NF system. Therefore, a de-embedding process has to be implemented. This can be achieved using the equation below

$$[C_R] = [C_{RBA}] - [T_{RB}] \cdot [C_A][T_{RB}]^H - [T_R] \cdot [C_B][T_R]^H \quad (12)$$

where $[C_B]$ is the noise correlation matrix of the bondwire and can be obtained from (6) with its S-parameters (S_B) that can be achieved using a numerical method or a VNA. Further discussion about this will be given in the next section. $[C_{RBA}]$ is the noise correlation matrix of the cascaded verification device, the bondwire and the auxiliary device. $[T_{RB}]$ is the cascaded T-parameter of the verification device and the bondwire network. Once the noise correlation matrix of the reference device is available, we can compare the reference value F_s and the measured noise figure (F_m).

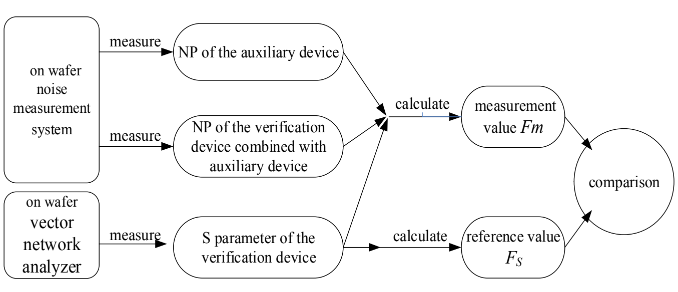


Fig. 3. Illustration of the proposed verification procedure for on-wafer NF measurement system.

III. Experimental Results

The Thru-Reflect-Line (TRL) calibration method was used to calibrate the on-wafer *S*-parameter measurement system. As shown in Fig. 2 the reference planes for the attenuator are A and B and the reference planes for the LNA are C and D. The two pairs of pads and the bondwire forms the bondwire network whose reference planes are B and C. The frequency of interest is between 2 GHz and 20 GHz.

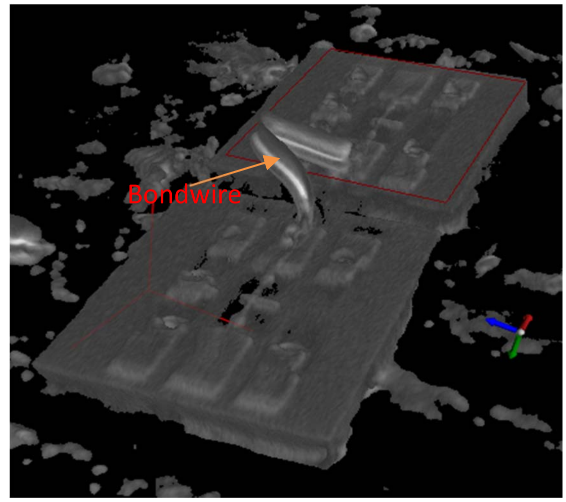


Fig. 4. The reconstructed 3D image of the bondwire obtained from using the X-ray computation tomography at the UK National Physical Laboratory.

Full-wave simulation on the bondwire was carried out using Computer Simulation Technology (CST) Microwave Studio. Due to the nature of bondwire which could be shaped arbitrarily, the actual configuration has to be profiled after it being formed. We used X-ray Computed Tomography (XCT) to characterize the profile of the bondwire. Fig. 4 shows the reconstructed 3D image of the bondwire obtained using a XCT at UK National Physical Laboratory (NPL). The 3D image is subsequently imported into CST for EM simulation.

Two mismatched attenuators with 1 dB and 3 dB attenuations were used as the reference devices for this study. We compare the NFs of the attenuators measured using the noise option of the VNA with those calculated using S-parameters with and without the bondwire. Fig. 5 and Fig. 6 show F_m, the measured NF without de-embedding the bondwire, F'_m, the measured NF with the bondwire and F_s, the reference noise figure of the 1 dB and 3 dB attenuators, respectively. One can notice that F'_m and F_m differ slightly i.e. less than 0.05 dB for the 3 dB attenuator but much greater deviation i.e. 0.26 dB for the 1 dB attenuator. This indicates that the influence of the bondwire decreases as the attenuation of the attenuator therefore the NFs increases. In addition, it is noted that for the 1dB attenuator the maximum deviation between the measured and reference NFs is 0.26 dB, which is much greater than the general noise measurement uncertainty i.e. 0.15 dB. Therefore, it is necessary to remove the excessive noise created by the bondwire in the verification method for the on-wafer noise figure measurement system. The discrepancy between the measured F_s and F'_m is mainly caused by the uncertainty of the noise measurement system; on the contrary, the difference between F_s and F_m is due to both the uncertainty of the measurement system and the noise contribution from the bondwire. It is obvious that the noise contribution from the bondwire leads to higher discrepancy as the attenuation decreases. The influence of the bondwire increases as the NF decreases and the measurement frequency increases.

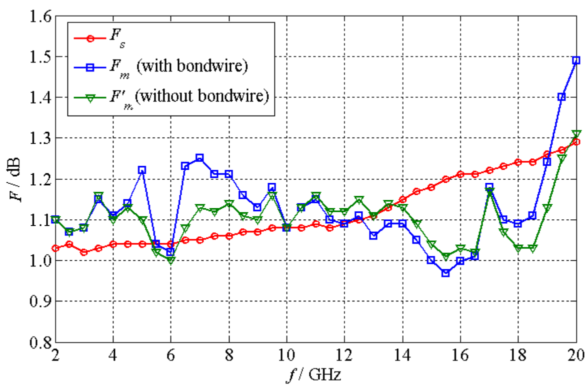


Fig. 5. Comparisons between the measured NFs with and without the bondwire and the reference value of the 1 dB attenuator.

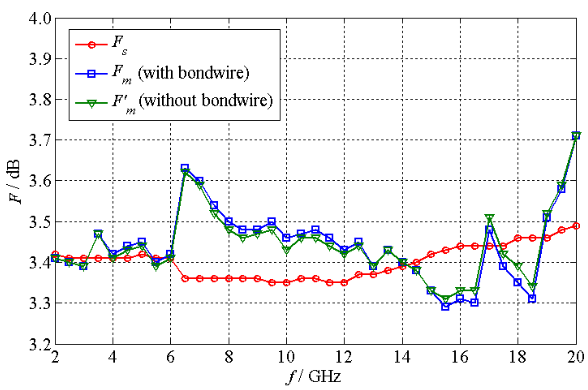


Fig. 6. Comparisons between the measured NFs with and without the bondwire and the reference value of the 3 dB attenuator.

IV. Conclusion

This paper presents the development of a cascaded on-wafer verification network and a verification procedure for on-wafer noise figure measurement systems. The cascaded network consists of a mismatched attenuator and a LNA. The attenuator and the LNA are linked with a bondwire. This design allows measurements of individual devices to be carried out as how the verification is performed for the coaxial configuration. We also proposed to use the passive device as the reference device for the verification procedure. Two mismatched attenuators were used as the reference devices. The experimental results show that the measured NFs have a good agreement with the references for both the 1 dB and 3 dB attenuators as long as the effect of bondwire is removed. It has also shown that consistent results have been achieved by using attenuators as the reference devices and a low noise amplifier as an auxiliary device. This approves that the proposed verification technique is reliable.

Acknowledgement

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References

[1] "Keysight Technologies High-Accuracy Noise Figure Measurements Using the PNA-X Series Network Analyzer," Keysight, Santa Rosa, California, USA. Available:http://literature.cdn.keysight.com/litweb/pdf/5990-5800EN.pdf

[2] A. Frazer and E. Strid, "Repeatability and verification of on-wafer noise parameter measurements," *Microwave J.*, pp. 172-176, Nov. 1988.

[3] A. C. Davidson, B. W. Leake, and E. Strid, "Accuracy improvements in microwave noise parameter measurement," *IEEE Trans. Microw. Theory Tech.*, vol. 37, no.12, pp.1973-1978, Dec. 1989.

[4] L. Escotte, R. Plana, J. Rayssac, O. Llopis, and J. Graffeuil, "Using cold FET to check accuracy of microwave noise parameter test set," *Electronic Letters*, vol. 27, no. 10, pp. 833-835, May 1991.

[5] A. Boudiaf and A. Scavennec, "Experimental investigation of on-wafer noise parameter measurement accuracy," in Proc. 47th ARFTG Conf. Dig., San Francisco, CA, Jun 1996, pp. 20-21.

[6] H. Bosma, "On the theory of linear noisy systems," PhD thesis, Philips Res. Repts. Suppl. Jan. 1967. Available online: https://pure.tue.nl/ws/files/3581427/109175.pdf

[7] E. C. Valk, D. Routledge, J. F. Vaneldik, and T. L. Landecker, "De-embedding two-port noise parameters using a noise wave model," *IEEE Trans. Instrum.Meas.*, vol. 37, no. 2, pp.195-200, Jun. 1988.

[8] K. Wong, R. Pollard, B. Shoulders, and L. Rhymes, "Using a mismatch transmission line to verify accuracy of a high performance noise figure measurement system," in Proc. 69th ARFTG Conf. Dig., Honolulu, HI, Jun. 2007, pp. 170–174.

[9] S. Van den Bosch, and L. Martens, "Deriving error bounds on measured noise factors using active device verification," in Proc. 54th ARFTG Conf. Dig., Atlanta, GA, Dec. 1999, pp. 116–121.

[10] V. Adamian and R. Fenton, "Verification of the noise parameter instrumentation, " in Proc. 49th ARFTG Conf. Dig., Denver, CO, Jun. 1997, pp.181-190.

[11] J. Randa, J. Dunsmore, D. Gu, et al., "Verification of noise-parameter measurements and uncertainties," *IEEE Trans. Instrum.Meas.*, vol. 60, no. 11, pp.3685-3693, 2011.

[12] D. Gu, J. Randa, R. Billinger, and D. K. Walker, "A verification method for noise-temperature measurements on cryogenic low-noise amplifiers," in Proc. Of Precision Electromagnetic Measurements (CPEM), Washington, USA, Jul. 2012, pp. 32-33.

[13] "Broadband low noise amplifiers," Cernex. Sunnyvale, California, USA. Available: http://www.cernex.com/PRODUCTS_NEW/Amplifier-PDF/BROADBAND%20LOW%20NOISE%20AMPLIFIERS.pdf

[14] H. A. Haus, "Optimum noise performance of optical amplifiers," *IEEE J. Quantum Electro.*, vol. 37, no. 6, pp.813-823, Jun. 2001.