

# Improved Y Factor Noise Measurement Using the Second Stage Contribution to Advantage

Alan M. Victor\*, *Member IEEE* and Michael B. Steer\*\*, *Fellow IEEE*

\* Harris Microwave Communications Division, \*\*Electrical and Computer Engineering Department  
North Carolina State University, Raleigh, \*\*NC 27695-7914 email: avictor@harris.com

**Abstract**— The ultimate limitation to characterizing noise in microwave amplifiers derives from the noise inserted by the front-end of the measurement set. Typically a high-gain low noise preamplifier is used in the measurement set to improve accuracy. Even then there is a limit to the minimum noise factor that can be measured. In this paper an extended Y-factor noise measurement technique is presented that utilizes an amplifier stage identical and in addition to the amplifier under test to enhance measurement accuracy. Utilizing a calibrated noise source, the output noise power of first a forward cascade of the two amplifiers is measured and then that when the amplifiers are arranged in reverse cascade. The use of a spectrum analyzer or power meter with a readily measured change in noise power reading is required as well as a calibrated noise source.

**Index Terms**—Cascade noise, LNA, noise measure, noise figure, noise factor, Y factor method.

## I. INTRODUCTION

THE Y-factor method is the basis of modern automatic noise figure measurement systems. The technique involves measuring the noise power at the output of a Device Under Test (DUT) when two different noise sources are attached to the input of the DUT [1]. The manual form of the Y-factor method is commonly used at microwave and millimeter-wave frequencies above the Intermediate frequency (IF) of automatic systems and also for spot noise figure measurements. The method is dependent on the accuracy of gain measurement, the ability to generate precise levels of excess noise power, and the sensitivity of noise power measurement. Gain and noise power measurement are subtly different with gain generally a coherent measurement while the noise power measurement is necessarily incoherent. In both the automatic and manual systems the measurement setup is a cascade system in which the DUT is the first stage and the test set is the last and usually second set. If the last stage is also the second the noise contribution of the test is only negligible if the gain of the DUT is high. Alternatively, it is common practice to insert a low-noise high-gain preamplifier between the stages [2]. Very often a suitable pre-amplifier is not available and this creates problems when the DUT has only low to moderate gain. As an alternative we propose the use of an additional amplifier stage that is the second stage in a forward cascade with the DUT and also switched with the DUT in a reverse cascade configuration. Therefore, a duplicate of the amplifier under test (the DUT) is utilized. The

augmented Y-parameter method presented here yields accurate noise characterization of both stages and can be used in either a manual or automatic noise characterization setup.

## II. Y-FACTOR FRAMEWORK

The impact of noise on system performance is quantified by the Signal to Noise Ratio (SNR) where  $SNR = S/N$ ,  $S$  is the signal power, and  $N$  is the noise power. Consequently the contribution to noise of a DUT is captured by the noise factor  $F$  which is the ratio of the input to the output SNR's:

$$F \equiv \frac{SNR_{IN}}{SNR_{OUT}} = \left( \frac{S_{IN}/N_{IN}}{S_{OUT}/N_{OUT}} \right) \quad (1)$$

where the subscripts IN and OUT denote the input and output of the DUT respectively. Under matched conditions the available gain of the DUT is

$$G \equiv S_{OUT}/S_{IN} \quad (2)$$

and so signal power can be eliminated from the expression for noise factor by combining (1) and (2):

$$F = \frac{N_{OUT}}{N_{IN}G} \quad (3)$$

The output noise is larger than the amplified input noise because of the noise inserted by the DUT. Denoting the component of the output noise power due solely to the DUT by  $N_D$ , the output noise power is

$$N_{OUT} = N_{IN}G + N_D = N_{IN}GF \quad (3)$$

The final component of our development is noting the input noise power is related to the temperature of the input match so that  $N_{IN} = kTB$  where  $k$  is Boltzmann's constant and  $B$  is the measurement bandwidth. Conventionally  $F$  is referenced to ambient room temperature  $T_0$  (specifically the input noise temperature is  $T_0$ ) and so

$$N_D = kT_0BG(F - 1) \quad (4)$$

In the Y-factor method two noise sources with noise temperatures  $T_1$  and  $T_2$  (with  $T_2 > T_1$ ) are applied to the DUT and the corresponding output noise powers  $N_1$  and  $N_2$  measured. This leads to the Y-factor, which is defined as  $Y \equiv N_2 / N_1$ . For one of these noise states an off-condition is generally used where  $T_1 = T_0$  and so the ‘off’ power is

$$N_1 = kT_0BG + N_D = kT_0BG + kT_0B(F-1). \quad (5)$$

The second noise source, with noise temperature  $T_2$ , produces calibrated excess noise and the power under these conditions is called the ‘on’ power:

$$N_2 = kT_2BG + N_D = kT_2BG + kT_0B(F-1) \quad (6)$$

Combining (4), (5) and (6) yields

$$F \approx \frac{T_2 - T_0}{T_0(Y-1)}. \quad (7)$$

Expressing (8) in decibels and integrating (or measuring) over the system bandwidth yields the Noise Figure

$$\text{NF} = 10 \log(F) = \text{ENR}_{\text{dB}} - 10 \log(Y-1). \quad (8)$$

where  $\text{ENR}_{\text{dB}} = 10 \log_{10}[(T_2 - T_0)/T_0]$  is the Excess Noise Ratio in decibels of the calibrated noise source.

One of the factors that affect the accuracy of noise figure determination is noise originating neither in the DUT nor in the input to the DUT [3]. Of particular concern is noise power generated in the measurement test set. This leads to an error sometimes referred to as the second-stage contribution effect. This is a particularly important issue when measuring the noise figure of low-gain devices as then the noise contribution of the second stage can be significant. It is further exacerbated when measuring the noise figures of microwave and millimeter-wave amplifiers as then down-conversion to an intermediate frequency is used leads to additional noise contribution and bandwidth limitations. One approach to minimizing this error is the insertion of a high-gain low-noise amplifier — we will refer to this as the instrumentation amplifier — between the DUT and the test set. The noise figure of the instrumentation amplifier should be known precisely if its introduced error is to be removed from the raw noise figure measurement. Problems arise in how the noise figure of the instrumentation amplifier can be measured for the particular power levels and bandwidths of the DUT. In the extended Y-factor measurement technique presented here, an instrumentation amplifier is not required. The technique relies instead on having two amplifier stages although they need not be identical and the system measurement bandwidth is constant and established by the test set, spectrum analyzer or suitable band-limited power meter.

### III. EXTENDING THE Y-FACTOR TECHNIQUE

The extended Y-Factor technique utilizes two DUTs in a two-stage cascade first with one arrangement of the DUTs and then with the alternative or reverse cascade. The technique makes use of the cascaded noise factor operation twice. Fig. 1 illustrates the test setup with two possible arrangements of the cascaded DUTs. In Fig. 1 the spectrum analyzer is configured to measure noise power (normalized to a 1 Hz bandwidth) using the marker noise mode. In our work 10 readings are averaged to obtain a stable value. Other methods for reading noise power can be used but the marker noise mode is quick, convenient, and a standard option on spectrum analyzers.

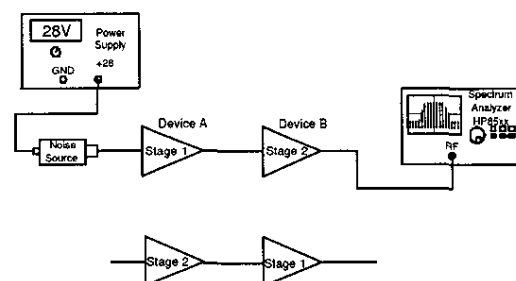


Fig. 1: Y-factor test set actively incorporating the second stage contribution effect.

The individual noise factors of the DUTs for a cascaded system with DUT A followed by DUT B are denoted by  $F_{1A}$  and  $F_{2B}$ , and the cascade with DUT B followed by DUT A is identified by  $F_{1B}$  and  $F_{2A}$ . Correspondingly, the total noise factors of the two-cascaded systems are denoted  $F_{TA}$  and  $F_{TB}$  according to whether DUT A or DUT B is the first stage. Using Friis’ formula we can write

$$F_{TA} = F_{1A} + (F_{2B} - 1)/G_{1A} \quad (9)$$

and

$$F_{TB} = F_{1B} + (F_{2A} - 1)/G_{1B}. \quad (10)$$

Here the first subscript refers to the position in the cascade (either first or second stage), and the second subscript identifies the particular DUT (either A or B). Also  $G_x$  is the gain of an individual stage. The technique presumes that the parameters of the DUTs are invariant of their position in the cascade so that  $F_{1A} = F_{2A} = F_A$  and  $F_{1B} = F_{2B} = F_B$ , as well as  $G_{1A} = G_{2A} = G_A$  and  $G_{1B} = G_{2B} = G_B$ . Equations (9) and (10) can now be solved simultaneously for the unknown noise factors of the two stages:

$$F_B = [F_{TB}G_A G_B - G_A(1 - F_{TA}) - 1] / (G_A G_B) \quad (11)$$

and

$$F_A = [F_{TA}G_A - F_B + 1] / G_A \quad (12)$$

So with the gains of the two stages measured independently, the noise factors of the two stages can be determined from the measured noise factors,  $F_{TA}$  and  $F_{TB}$ , of the stages arranged in first one cascade, and then in the reverse cascade arrangement respectively. From these the noise factors of each of the stages can be derived.

In the special situation of matched DUTs where the noise and gain of the two stages are identical (so that  $F_A = F_B = F$  and  $G_A = G_B = G$ ) then we will have  $F_{TA} = F_{TB} = F_T$  and the calculations simplify to yield the noise factor of a stage:

$$F = \frac{GF_T}{G^2 + 1} \quad (13)$$

One of the assumptions of the augmented Y-factor approach is that the gain and noise of the stages are invariant with the position of the stages in the cascade. Any departure will result in an error. One manner to reduce sensitivity to matching conditions is to provide one device with either small attenuators or low loss isolators at the input and output. Another method is to use a test set amplifier with good input and output return loss commensurate with low noise factor.

#### IV. MEASUREMENT PROCEDURE-EXAMPLE

The procedure requires accurate measurement of gain and noise power ratio. In common with the conventional Y-factor noise characterization procedure a well-calibrated noise source is essential. The method has been used routinely to characterize the noise performance of a variety of microwave and millimeter-wave amplifiers. In this section we compare noise characterizations obtained using the augmented Y-factor method and the conventional approach using an automated noise measurement system.

The validity of the method was explored using 1.5 GHz GaAs MMIC devices with a total gain of 28 dB. The MMIC incorporated a band pass input match to optimize return loss and noise figure. Two noise sources with different ENR were used for the "on" state and these sources functioned as ambient sources in the "off" state. Two MMICs were used to realize the two amplifier stages. The noise factors of the forward and reverse cascades were nearly identical. Comparisons of the noise figure extracted using the augmented Y-factor method and that measured using an automated noise measurement are presented in Fig. 2. It is noted that good agreement is obtained in the automated noise figure measurement for both the low and high ENR noise sources at amplifier band center. As well, there is good agreement between the results obtained using the extended Y-factor method and that from the automated test set. The agreement is particularly good near the band center where return loss is also at a minimum. Near the band edges the agreement is not as good as return loss degrades and, presumably, noise characteristics are dependent on the order of the stages in the cascade. The disparity is attributed to dependency on the impedance of the noise source. A noise source with low ENR is preferred as, relative to the high ENR source, it has an input impedance that deviates less between the on and off states [4,5].

In a second test an amplifier with 28 dB gain was used instead of the second matched MMIC. This amplifier

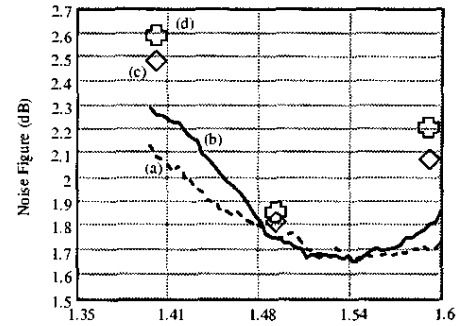


Fig. 2. Measured noise figure (dB) vs. frequency (GHz) obtained with the automated noise measurement set, (a) low ENR ( $= 5.2$ dB) noise source, and (b) high ENR ( $= 15.1$  dB) noise source; and obtained using the augmented Y-factor method, (c) the augmented Y-factor method with the low ENR source, and (d) with the high ENR source.

corresponds to an instrumentation amplifier that is commonly used as a pre driver before a noise measurement system. In this case the Y-factor method alone provided a minimum noise figure of 4.1 dB at 1.49 GHz. In contrast the augmented Y-factor method yielded a noise figure of 1.8 dB, which is close to the other measurements of noise figure shown in Fig. 2. This significant discrepancy is an indication that the second stage contribution effect can be significant.

#### V. CONCLUSIONS

A noise measurement procedure that augments the traditional Y-factor method was presented. Central to the method is the use of two stages that can be arranged in, first, a forward cascade and then in the reverse cascade. Enhanced measurement fidelity is obtained by accounting for the second stage contribution to noise. In effect the contribution of the second stage is shifted from the test set to two cascaded DUT units. This is accomplished by applying the Y-factor measurement twice for the amplifier cascade and the reverse cascade.

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